AN ALL-HAZARDS VULNERABILITY ASSESSMENT OF ARTHUR'S PASS TOWNSHIP, SOUTH ISLAND, NEW ZEALAND

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Kate Dundas

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FRONTISPIECE

Arthur's Pass township, South Island, New Zealand

ABSTRACT

Arthur's Pass township, located close to the Main Divide of the central Southern Alps, is highly exposed to natural hazards and has been affected by hazard events since it was founded in 1906. The village is a small alpine township, with a permanent resident population of approximately 54. Its location within the Arthur's Pass National Park and on the main road between the east and west coasts of the South Island makes it popular with tourists, trampers, climbers and skiers, which can expand the local population to up to 500 people. Its position on the Bealey River floodplain within a highly dynamic tectonic and geomorphic environment makes it vulnerable to earthquakes, landslides, rockfalls, debris flows, heavy rain and snow, river flooding and riverbed erosion.

Previous investigations on natural hazards in the area are limited to the Otira Gorge and State Highway 73, with little focus on hazards affecting the village area. Natural hazard events are persistent and frequent in the Arthur's Pass region and the village is susceptible to being isolated from external resources during and after a disaster, making it necessary for the village to be self-sufficient during a large-scale disaster.

The hazards were identified and analysed using aerial photographs and satellite images, historical data, supported by in-field reconnaissance at various times of the year to record seasonal changes. Hazard mapping used the same methods to illustrate the spatial and volumetric hazard changes over a range of time scales; >2% annual probability of occurrence (0-50 years recurrence interval), 2%-0.2% annual probability of occurrence (50-500 years recurrence interval) and <0.2% annual probability of occurrence (500+ years recurrence interval). The hazard maps show that that most hazards are not restricted to a specific temporal or spatial scale, and that they are often interdependent.

It is difficult to determine the precise effects that climate change and global warming will have on natural hazards, but they are expected to increase the unpredictability of hazard events and alter weather patterns significantly in the long-term.

A visitor questionnaire undertaken in the village indicated that many visitors do not regard the hazards as severe enough to represent a legitimate threat; hence the public perceptions of natural hazards are affecting the vulnerability of the village. Additionally, many people do not feel confident that they would know what to do if a disaster did occur in the village. This level of awareness can be improved by providing more information to visitors and displaying details on emergency procedures.

The village does not currently have an emergency plan that specifies particular preparedness and response procedures; it relies heavily on a plan adapted from Mt. Cook/Aoraki village. Current emergency management in the village could be improved by the production of an emergency plan specifically for the region, the use of education schemes and information sessions, and the installation of warning signs.

The provision of this detailed hazard investigation and hazard maps is intended to assist emergency managers to identify, prioritise, mitigate the hazards to reduce the vulnerability of the village to natural hazards in the short- and long-terms.

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>2% annual exceedence probability (0-50 year return period)

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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

Arthur's Pass is a small alpine community in the central Southern Alps of New Zealand, positioned along the bottom of the Bealey Valley, 5km south of the Main Divide.

Natural hazards in Arthur's Pass have the potential to cause extensive damage and disruptions to the local township. The hazards include, but are not limited to, earthquakes, flooding and debris flows, landslides, river processes and avalanches. These natural hazards increase the vulnerability of the town as a major tourist centre throughout the year and as the major transport route between the east and west coasts.

To date, very little investigation has been done to quantify the risks, ascertain exactly where the hazards exist and their probability of occurrence. There is currently only minimal monitoring of the known hazards in the area and work is needed to focus on the identification, examination and categorisation of the natural threats that could impact on the Arthur's Pass township. Additionally, the community awareness and perception of the hazard risk is yet to be determined, and this is an aspect that could have major consequences on response times and community recovery in the event of a major disaster.

Since the establishment of the town in 1906, only a limited amount of research has been carried out that applies directly to the Arthur's Pass village. Much of the information that does exist relates to the threat to State Highway 73 or examination of the predominant geological features in the Arthur's Pass National Park, such as active fault lines and glacial moraines. Investigations carried out in the park typically focus on the Otira Gorge section of highway several kilometres north of the township and neglect the natural hazards as a legitimate threat to Arthur's Pass village. Therefore a thorough investigation of these hazards and their potential impacts on the Arthur's Pass community is warranted to assist emergency planners in better preparing the village to cope with a natural disaster.

1.2 AIM AND LIMIT OF SCOPE

The aim of this research is to provide a detailed vulnerability investigation of the natural hazards directly influencing the Arthur's Pass township and assess the societal perception of the risks, in order to enable local organisations and governing bodies to make informed decisions about how to mitigate the hazards and better prepare for a disaster. On account of this, the research aims to not only provide a scientific approach to hazard identification and examination, but it also offers a social perspective of hazard impacts.

The assessment aims to focus on the hazards directly affecting the village area but in many cases it is necessary to consider processes taking place over a much greater area, especially when hazards are sourced distantly or have widespread consequences. For this reason, an assessment of the hazards throughout the Arthur's Pass National Park, that have the potential to impact recreational users of the park outside the village area, have been included as part of the analysis.

The study of forthcoming hazard events is greatly constrained by the availability of historical and field data, which limits the scope of the investigation. Detailed records of previous events rarely exist so the reliability of hazard estimates based on historical data is restricted. Hazard occurrences are expected to continue indefinitely, so the research has not been limited to hazards taking place over a specific time scale; instead it divides hazard zonation and mapping into three main time frames.

Whilst every attempt has been made to accurately portray hazard zones within the Arthur's Pass township area and its surrounds, the research is by no means exhaustive and should not be used as a substitute for in depth engineering and geophysical investigations of specific sites. The hazard analysis and mapping is expected to be used as a guide to assist future emergency planners of the village to make better informed decisions about hazard management at Arthur's Pass.

1.4 THESIS STRUCTURE

To achieve the research aim, hazards have been classified into four main groups for the main body of the project, and then discussed collectively in the final chapters (Figure 1.1).

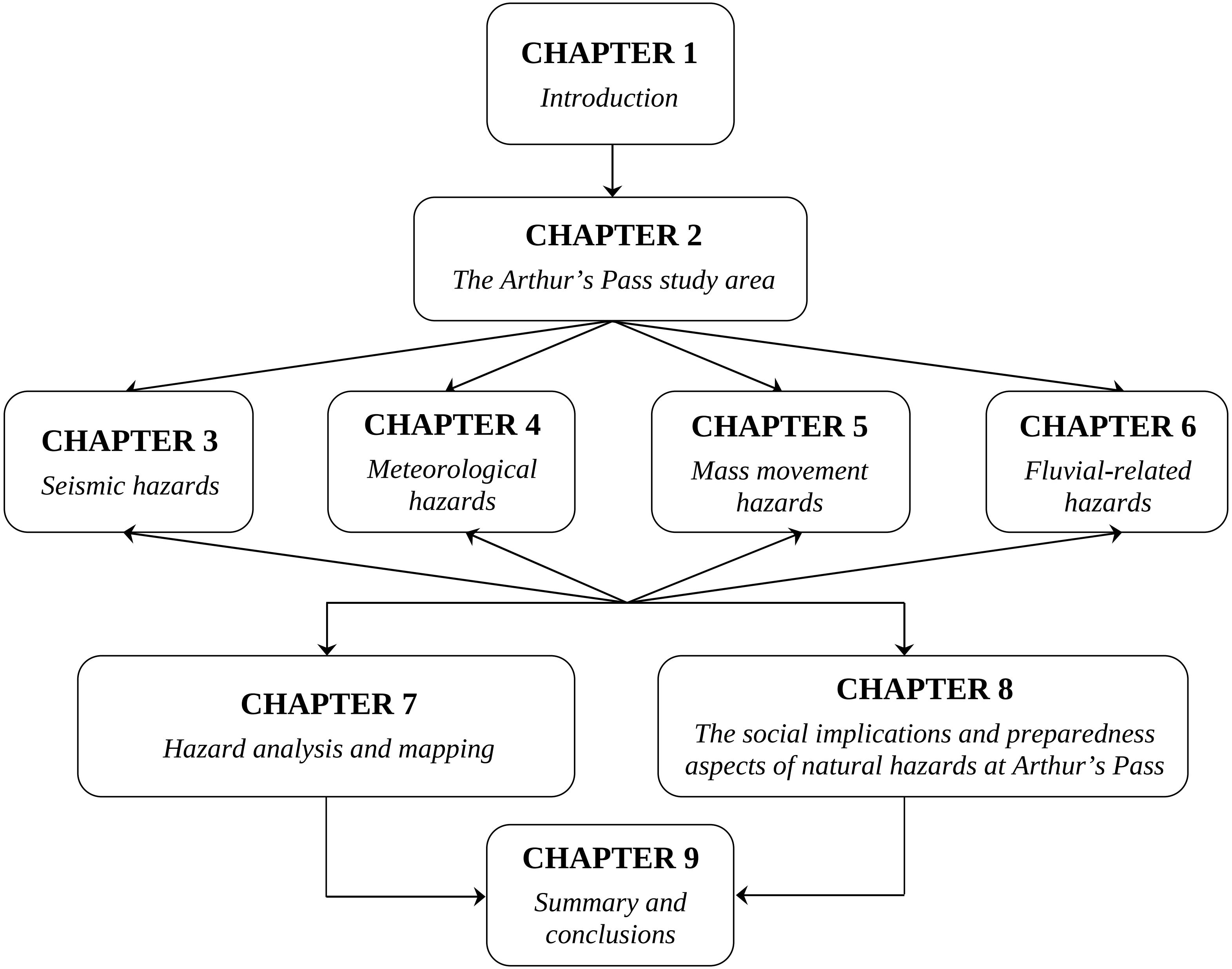

Figure 1. 2. The organisational structure of this study.

Chapter 2 gives an overview of the Arthur's Pass study area in terms of its location, history, and physical and environmental attributes such as geology, climate and local vegetation. It reviews existing research on various hazard aspects within the Arthur's Pass National Park and discusses the methods of research used to complete the hazard vulnerability assessment.

Chapters 3 to 6 are hazard assessment chapters; each deals with a different hazard type. The overall hazard assessment structure has been adapted from a hazard reduction methodology set forth by Brabhaharan (1996). Each chapter aims to:

1. Identify and explain the natural hazard types that exist in the Arthur's Pass study area.
2. Describe historical hazard events that have occurred in the study area and may have the potential to recur.
3. Carry out site-specific hazard investigations to identify hazard zones.
4. Consider the risk and impact of the hazard on the community and its infrastructure.
5. Examine current management methods and consider other mitigation options and whether mitigation is justifiable.

Chapter 3 analyses the local and regional seismic hazards affecting Arthur's Pass, and relies heavily on historical earthquake data to indicate what is to be expected in the future. Chapter 4 analyses the meteorological hazards to which the Arthur's Pass National Park is exposed, including the effects of seasonal weather patterns and climate change. Chapters 3 and 4 represent the "driving" hazards; usually the initiating forces of other natural hazard types.

Chapter 5 analyses the mass movement hazards throughout the village area and Arthur's Pass National Park; these occur on a variety of spatial, temporal and volumetric scales. Chapter 6 analyses the hazards related to the fluvial system in the Bealey Valley, ranging from flooding to riverbed erosion and aggradation. Chapters 5 and 6 characterise the "response" hazards, which are easily influenced by other processes with hazard zones.

Chapter 7 collates all the hazard information from Chapters 3 to 6 to assess the vulnerability of the Arthur's Pass community and discuss the interrelationships that exist between different hazard types. This section culminates in a description of the uses of hazard mapping as an aid to risk reduction and an explanation of the methodology used to construct a series of hazard maps for the Arthur's Pass region.

Chapter 8 researches the social implications of natural hazards to the community using a visitor questionnaire to assess public risk perceptions. These results in addition to the results from the hazard analysis in Chapters 3 to 6 have been used to evaluate the effectiveness of the current emergency plan in the village and provide recommendations for future revisions to the plan. Chapter 9 follows with a summary of the research conclusions explaining the significance of the study results.

1.5 TERMINOLOGY - RISK, HAZARD AND VULNERABILITY

International terminology used to define natural hazards and their processes can be highly variable and ambiguous. Because so many hazard types exist in the Arthur's Pass region, it is necessary to define hazard, risk and vulnerability as they apply to the Arthur's Pass setting, because these three components form the most fundamental relationship in hazard assessment. Individual hazard definitions are outlined in Chapters 3 to 6.

Risk can be very basically explained as a product of the hazard and vulnerability of a region.

Risk = Vulnerability x Hazard

Risk, as it pertains to this hazard assessment, is defined as 'the chance of something of human value being exposed to a natural hazard with negative outcomes' (Keey, 2000; K. Smith, 2004). Furthermore, according to Elms (1998), there are three aspects of risk:

- the possibility or probability of a hazard event occurring;
- the consequences of the event should it happen,
- the context of the hazard.

Vulnerability is a condition determined by social, economic, physical and environmental factors that increases the susceptibility of a community to natural hazard processes (National Disaster Management Authority, 2006). To better understand the nature of risk and vulnerability with respect to natural hazards, Wisner et al (2004) describe the Pressure and Release Model; this suggests vulnerability is a result of underlying root causes spawned by limited access to power, structures, utilities and resources, often in politically and economically unstable territories. Vulnerability is boosted further by the introduction of dynamic pressures to the system. Pressures exist in the form of rapid urbanisation and population growth, devegetation, isolation and the lack of training, skills and ethical standards in threatened communities. When unsafe physical, economic, social and institutional conditions are added to the system the outcome is a highly exposed community with a very reduced capacity for disaster resilience and recovery (Wisner et al., 2004).

Hazard is best comprehended as a naturally occurring or human-induced process or event that has the ability to generate loss and damage in the future. A natural hazard is the causative factor in any natural disaster, and hazards to human life are rated as the highest priority ahead of environmental modification and property damage (K. Smith, 2004).

Risk is often used synonymously, albeit incorrectly, with hazard. They differ in that risk takes into account the extra implication of the chance of an event actually occurring (K. Smith, 2004) and portrays the human response to the hazard in question (Grant, 1998). A disaster is the realisation of a hazard and the consequences of a hazard event.

CHAPTER 2

THE ARTHUR'S PASS STUDY AREA

2.1 LOCATION AND STATISTICS

The Arthur's Pass township lies within the Southern Alps on the South Island of New Zealand at an altitude of between approximately 720m and 760m (Figure 2.1). The village is confined to a narrow valley on the western bank of the Bealey River between Mt. Aicken and Avalanche Peak. State Highway 73, which links the east and west coasts of the South Island, forms the main street of the town and provides the only inward and outward transport route other than the railway (Figure 2.2). The village has an areal extent of 0.6km^2 (300m by 2000m) and its location on the Bealey River floodplain makes it accessible for field work and mapping.

Arthur's Pass village lies within the Canterbury Region and is locally governed by Selwyn District Council. The most recent statistical examination of the Arthur's Pass village yielded a regional population count of 90, and a town population of 54 permanent residents (Brown, 2007). The majority of residents are occupied with running tourist services, namely accommodation, recreation and dining facilities (Department of Conservation, 2002).

The Department of Conservation records over 130 000 visitors each year within the Visitor Centre, and a road counter measures an annual traffic count of more than 250 000 vehicles through the town. Approximately 70-75% of visitors to the Arthur's Pass National Park arrive in private vehicles. The remainder travel either in tour groups on buses or on the train that connects Christchurch and Greymouth or through other means such as cycling or hitchhiking (Espiner & Simmons, 1998).

The village has its own police station, railway station, general store, chapel and helipad (for emergency rescue helicopters) and is the main administration centre for the Department of Conservation within the Arthur's Pass National Park. There are approximately 142 "habitable" buildings within the town boundaries, all of which are clearly numbered and correspond to details in the emergency response plan.

Figure 2. 1. The location of Arthur’s Pass village within the Southern Alps of New Zealand, along State Highway 73 (basemaps sourced from (GoogleMaps 2008)).

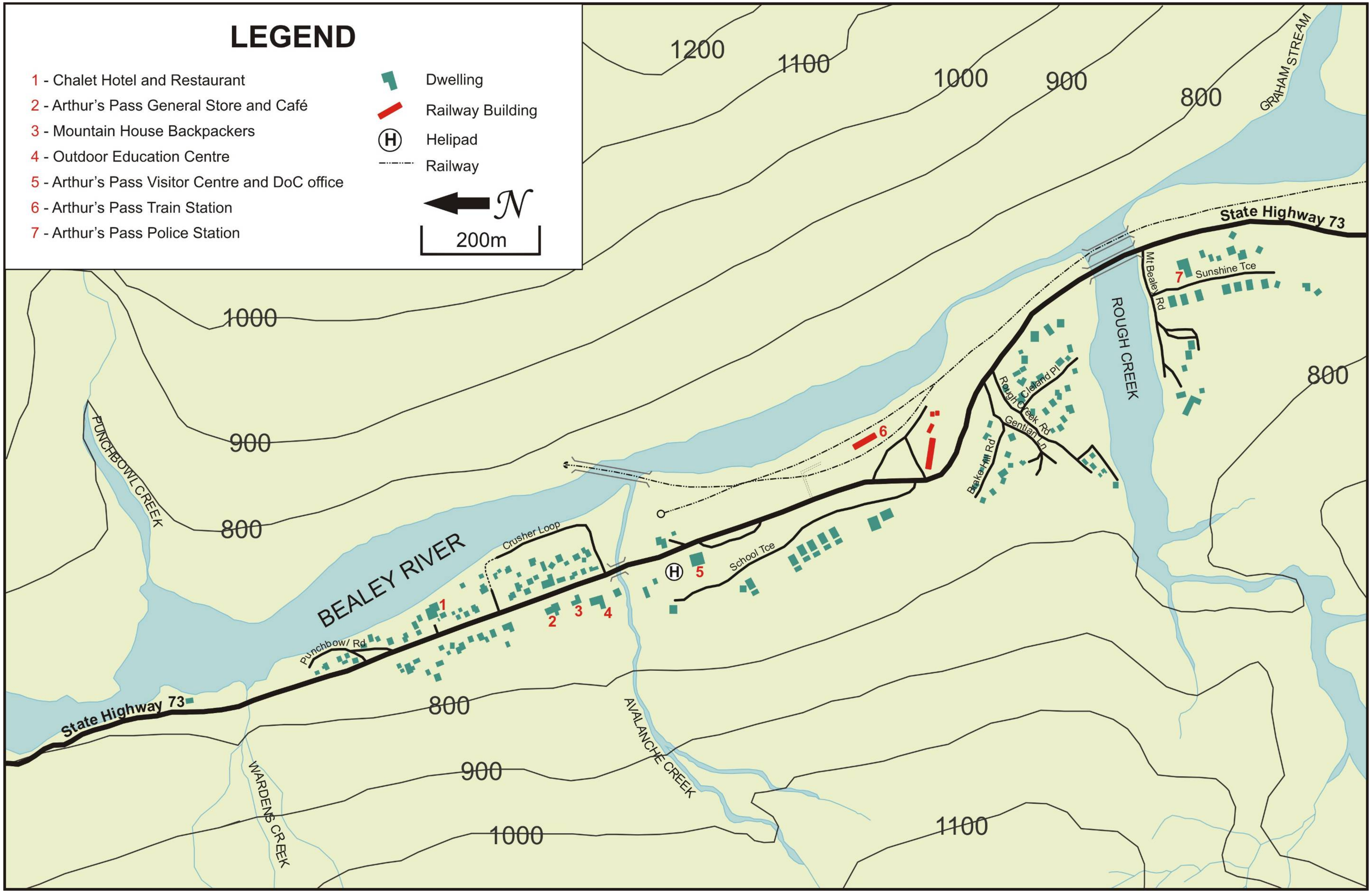

Figure 2. 2. Arthur's Pass village, along State Highway 73 through the Southern Alps, consisting of 142 'habitable' dwellings and a permanent resident population of 54.

The town is currently a major tourist centre because of its proximity to many recreational facilities. It is a starting point for the numerous tramping tracks that lie within Arthur's Pass National Park and is a base for people involved in mountaineering, rock-climbing, bird-watching, hunting and fishing. The Temple Basin ski field is a major drawcard for visitors during the winter months, which keeps the tourist population steady throughout the year. The recreational uses of Arthur's Pass National Park are shifting. Marked changes have occurred since the 1980's, when the recreational uses of the park were quite limited. In the last 25 years the types of activity possible in the park have diversified and new forms of activity have emerged, particularly for sports training purposes. The most common recreational activities undertaken by park visitors are day walks and sightseeing. Picnicking, camping and climbing are also popular pursuits in the Arthur's Pass area (Espiner & Simmons, 1998). These statistics may have implications on the nature of hazard and emergency management within the village and national park.

2.2 HISTORICAL REVIEW

The formation of the Arthur's Pass township (originally called Bealey Flat) happened out of necessity, rather than as a matter of preference. The pass was originally used by Maori traders as a route through the Southern Alps. Many years later, European settlers discovered Arthur's Pass when trying to find an alternative route to the west coast in the midst of the gold rush. The route in use today came into existence when a surveyor named Arthur Dobson set out in 1864 with the aim of finding a suitable crossing of the Southern Alps. After only barely crossing the pass on horseback, he came to the conclusion that the conditions for road engineering were nearly impossible (Taylor, 2005). This did not deter the Canterbury provincial engineer and it was decided that a road would be constructed through the pass to the west coast, and work began in 1865 (Department of Conservation, 2006). Several decades later in 1907, the Midland Railway was built to link Christchurch and Greymouth. The project was completed fairly quickly with the exception of the section between Otira and Arthur's Pass, in which a tunnel was needed through highly weathered and metamorphosed rock.

The township itself formed as a settlement in 1906 for labourers working on the Otira tunnel (Department of Conservation, 2006). It was relocated to its current location after conditions at nearby Klondyke Corner were found to be quite inhospitable. The initial buildings were flimsy and often damaged during storms or floods. Gradually the town became more permanent as a rail and coach interchange until the tunnel was completed in 1923, by which time people had started to visit the area for its beauty and recreational potential. Despite the subsequent closure of the horse-drawn coach houses, Arthur's Pass village was further popularised by the formation of the Arthur's Pass National Park in 1929, when the town became the base for those interested in outdoor activities. The area became known for its tramping, mountaineering, skiing, bird-watching and hunting opportunities and attracted many enthusiasts. Since then, the area has continued to be a tourist and recreational centre as well as a popular stop on road and rail journeys between the east and west coasts.

2.3 PHYSICAL AND ENVIRONMENTAL ATTRIBUTES

It is vital to have knowledge of the local physical setting in order to understand why the hazards exist where they do. Cave (1982) suggests that there are three main factors that influence the distribution and occurrence of natural hazards. Firstly, one must be aware of the current tectonic setting and be able to apply it to hazard assessment. Secondly, a familiarity with the geological features in the area is necessary because various rock types behave in very different ways when stress is applied to them. Lastly, climatic conditions are typically a major control on whether an event will occur, as it can often act as a trigger or catalyst for a natural disaster. Other factors such as slope gradient and vegetation cover also contribute to landscape stability and they have been included in this section.

2.3.1 Geology

The numerous geological processes currently taking place are to a great extent responsible for the hazard issues observed in Arthur's Pass. One of the most important factors in this hazard identification is to recognise and understand the geological features of the Arthur's Pass region. Examination of the rock types and structures in the Arthur's Pass region gives an understanding of rock behaviour which can be applied to hazard analysis to determine the reaction of the landscape to future events.

2.3.1.1 Lithology

The rock sequence stretching along the entire length of the Southern Alps and Alpine Fault is geologically classified as the Torlesse Supergroup; a large sequence of sedimentary strata containing a diverse range of fossiliferous traces within layers of sandstone and mudstone. The sequence was formed sporadically over a long period of time between the late Carboniferous and early Cretaceous periods (Cave, 1987). Locally it is known as the Torlesse greywacke. The marine sediments comprising the Torlesse greywacke have been subjected to intense pressures during mountain building processes which has resulted in a folded, faulted and highly metamorphosed lithological sequence (Coates & Cox, 2002).

The Torlesse rocks within the Arthur's Pass National Park are further subdivided into zones that are based on the fossil remnants within the bedded sequences and the proportion of fine-grained siltstone and mudstone within the sandstone deposits (Cave, 1987). To the east of the regional unconformity defined by the Alpine Fault is the Terebellina Zone, which contains alternating beds of sandstone and siltstone with preserved fossils. Next to the Terebellina Zone is a smaller wedge of thick-bedded sandstone called the Hokonuia Zone. It is characterised by thin beds of poorly sorted sandstone with outcrops of conglomerates. Further east, a major section of the Arthur's Pass National Park contains thick sequences of homogeneous, cross-bedded and thick-bedded sandstone with thin, interbedded argillite deposits. This group has a relatively high content of bivalve fossils and some minor conglomerate deposits (Cave, 1987). It is collectively known as the Monotis Zone. The Arthur's Pass township lies across the Monotis Zone on a deposit of overlying alluvium from the Bealey River (Cave, 1979b).

The Arthur's Pass village is confined to the narrow floodplain of the Bealey River, where unconsolidated greywacke boulders are observed over much of the undeveloped land. The underlying Monotis Zone is younger than the geologically comparable Terebellina Zone, and contains different proportions of sandstone and siltstone which has become indurated to form argillites and lithified sandstones (Cave, 1987). Whitehouse and McSaveney (1992) suggest that the sandstone component of the Monotis Zone is as much as 70% in this region, as only thin beds of argillite separate the thick-bedded sandstones. The numerous specimens of the fossil bivalve *Monotis* have been used to accurately date the rocks to the late Triassic period, and at some localities around the National Park, preserved plant materials are found within siltstone and occasional sandstone deposits that represent a minor lithological group within the Monotis Zone (Cave, 1987). A limited number of conglomerate deposits and highly deformed syn-orogenic rocks (often called flysch deposits) have also been recorded in areas adjacent to the village such as on the flanks of Avalanche Peak and at Temple Basin (Odell, McCaskill, & Adams, 1966).

Several surficial deposits are observed in the Arthur's Pass village. Alluvial fan and riverbed sediments in the township vicinity cover a wide area and are generally unconsolidated. They are typically poorly sorted, ranging from fine-grained to boulder sized. River sediments are derived from greywacke bedrock and reflect many of the same lithological features as the surrounding mountains from which they came.

2.3.1.2 Structural Features

The Southern Alps are the region of maximum uplift in Canterbury and therefore the oldest rock formations are associated with this region compared to the plains and foothills (Yetton & McCahon, 2006). The rocks have been folded, faulted and tilted to produce textures that are synonymous with intense metamorphic processes. Rock outcrops in the region reveal significant jointing and weathering of the greywacke which make the rocks brittle and sometimes unstable. In his review of earthquake-generated landslides, Keefer (1984) describes the most susceptible rocks as those with acute weathering and intense jointing, fracturing and shearing. There have been numerous incidents of rockwall failures on many of the outcrops near the village which are responsible for the deposition of large volumes of material into the fluvial system.

Several active fault traces have been identified that have the potential to initiate hazards in the vicinity of Arthur's Pass village. Regional faults that lie within 25km of the village are the Alpine Fault, Harper Fault and Hope Fault. The Alpine and Hope Faults have a strike-slip structure and the Harper Fault is a thrust fault (Chamberlain, 1996). Historically they are all capable of producing fairly high magnitude earthquakes. On a more local scale, the Poulter Fault and Kelly Fault are both more than 10km away from the township but still represent a high seismic threat. The smaller and possibly less dangerous faults within the Selwyn District are those that exist less than 10km from the village. Examples of these include the Scott Fault, Punchbowl Fault Zone, Aicken O'Malley Fault Zone and the Red Rock Fault Zone (Cave, 1982). Additionally, several unnamed minor faults around the village also warrant investigation.

Ridge rent structures have been detected throughout the National Park; these are the result of the gravitational collapse of slopes along deep-seated surfaces of weakness. They are good indicators of fault zones that have the potential to generate rock avalanches in the future and highlight sites that should be monitored. Most ridge rents have been identified in the Otira Gorge but smaller numbers are observed in the mountains adjacent to the Arthur's Pass village.

2.3.2 Geomorphology

The town lies within a dynamic geomorphic system that can be quite unstable and easily influenced by outside factors, such as weather and climate anomalies and tectonic events that frequently occur in the Arthur's Pass region.

The section of the Bealey Valley in which the Arthur's Pass village lies is characterized by a very distinct geomorphological signature. The slopes are generally very steep and the Bealey River flows along a relatively wide riverbed and floodplain to form the base of the valley. In the upper reaches of the Bealey Valley the river follows the route carved by glacial advances (Paterson, 1996). The mountains surrounding the Arthur's Pass village rise to almost 2000m and the tributaries that feed the Bealey River are sourced from high in the catchment area and travel to the valley floor along very steep courses. Sharp ridges and basins with numerous scree deposits have developed on the upper reaches of the mountains and several of these areas have permanent snow accumulations or small glaciers associated with them (Paterson, 1996).

The processes operating in the Bealey Valley are somewhat different from those in the surrounding mountains, resulting in different geomorphologies. The valley floor comprises thick deposits of river debris and is comparatively flat. Furthermore, it contains residual fan accumulations from debris flow events and stream processes, in addition to deposits associated with rockfalls and glacial advances (Paterson, 1996). Several glacial moraines have been identified within the Bealey Valley that record minor Holocene advances during the Holocene period (Paterson, 1996). There is very little evidence of the deposits formed during the major Pleistocene glaciations; only the glacial features such as the steep, U-shaped valleys have been preserved (Paterson, 1996). Chinn (1975) further explains the existence of a series of lateral terminal moraines adjacent to where McGrath Stream intercepts the highway. This McGrath Advance, as it is known, was one of the most extensive advances in the area during the Holocene period and mostly occupied the upper Otira and Bealey Valleys and their bordering cirque basins (Cave, 1982).

2.3.3 Climate

Arthur's Pass has an alpine climate typical of mountainous regions (Figure 2.3A and B). The weather has the ability to change rapidly and without warning because of the high altitudes, which can make daily weather prediction difficult. The village is frequently exposed to north-west winds that bring huge deposits of rain or snow to the Main Divide before heading down the Canterbury Plains as warm, dry winds. High-intensity storms often unload large volumes of rainfall in a short period of time, thus concentrating the number of rain days during the year (Odell et al., 1966). Frosts occur throughout the year and nights are typically cold, with a high variation in daily maximum and minimum temperatures (Burrows, 1974). During winter, heavy snowfalls can blanket the town and increase the avalanche risk throughout the Arthur's Pass National Park.

2.3.3.1 Temperatures

Complete records of temperature conditions at Arthur's Pass date back to 1978, and are very well documented (National Institute of Water and Atmospheric Research, 2007) (Appendix A). The average maximum air temperature for any given year at the Arthur's Pass village is 12.0^{o}C and the average minimum air temperature is 3.2^{o}C (based on 1978-2006 data) (Table 2.1).

	Average Maximum Temperatures (^{o}C)	*Average Minimum Temperatures (^{o}C)*
January	18.0	7.8
February	18.0	7.8
March	15.6	6.2
April	12.6	3.6
May	9.4	1.8
June	6.7	-0.8
July	5.8	-2.0
August	7.3	-1.1
September	9.6	1.0
October	11.6	3.1
November	13.7	4.7
December	15.7	6.7
Average	***12.0***	***3.2***

Table 2. 1. The average monthly temperatures at Arthur's Pass village for the period 1978 to 2006 (NIWA 2007).

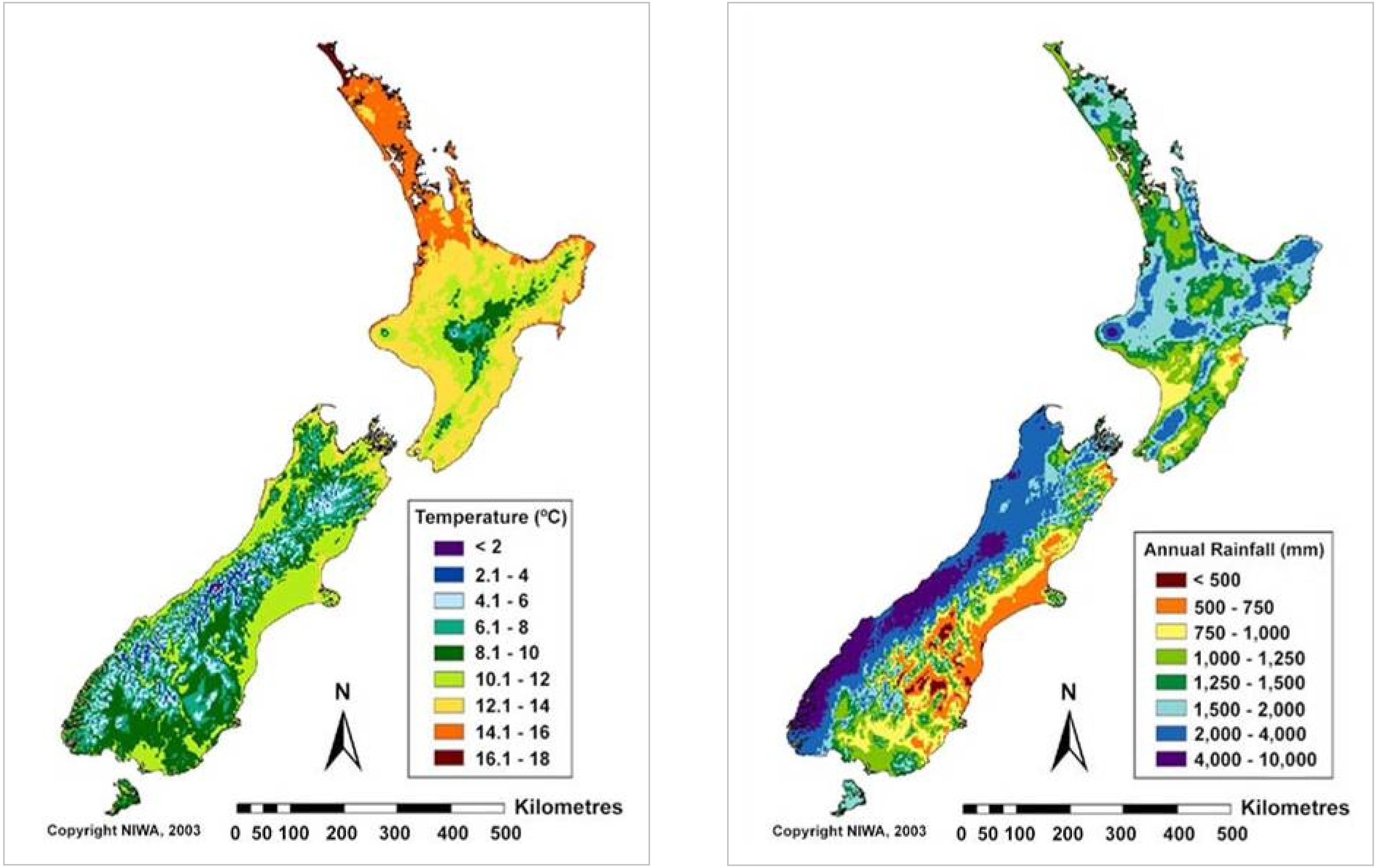

Figure 2. 3A and B. Climate patterns for New Zealand and the Arthur's Pass region between 1971 and 2000. **A.** Mean annual temperature. **B.** Mean annual rainfall (Arthur's Pass – 4375mm) (Mackintosh, 2001; National institute of Water and Atmospheric Research, 2003).

The highest average maximum temperature between 1978 and 2006 was 13.1^{o}C in 1999 and again in 2005. The lowest recorded average maximum was 11.0^{o}C in 1992. The highest average minimum temperature was 4.1^{o}C in 1998 and the lowest 2.2^{o}C in 1982.

Temperature variations between night and day can be quite extreme, and often severe frosts are followed by a day of intense sunshine. North-west winds are frequently channelled through the Bealey Valley and often lower the temperature in the township quite noticeably (Burrows, 1974).

2.3.3.2 Rainfall

Detailed daily rainfall records were obtained from the beginning of 1955 to the end of 2006 (Environment Canterbury, 2007), giving a total of 52 years of data. There are 177 days of rain in a typical year in Arthur's Pass village. Since 1955, the wettest year had 225 days of rain (1956) and the driest year had only 111 days of rain (1961). Over the last 52 years, the average has remained stable and not increased significantly (Appendix A). Based on daily rainfall data, the wettest month of the year is October. Periods of high rainfall are from September to December and throughout the month of May before the onset of snow. The average rainfall for these months ranges from 393.6mm to 447.0mm (Table 2.2).

	Average Monthly Rainfall (mm)
May	393.6
September	396.2
October	447.0
November	421.8
December	395.7

Table 2. 2. The wettest months of the year and their corresponding rainfall averages at Arthur's Pass village for the period 1955 to 2006 (Environment Canterbury, 2007).

The driest months are February and July, where rainfall averages are 266.7mm and 267.6mm respectively. These values are deceptively low, considering both months often have more than 300mm and February has had as much as 819.9mm in 1955. Similarly, the highest rainfall in July was up to 767.5mm as recently as 1998.

There is a slightly increasing trend in annual rainfall from 1955 to 2006. This could be partly attributed to small amounts of missing data due to malfunctions with recording instruments in the first few decades of data collection, but it corresponds to increasing maximum levels of the large lakes further south. Rainfall records are almost complete for the last 19 years with very little data missing. Consequently, the most recent entries are probably a more accurate representation of rainfall compared to the earlier records in the 1950's and 1960's, where large amounts of rainfall data have been intermittently lost. The annual rainfall average calculated from all rainfall measures is 4283.7mm. The calculated average for the last 19 years is 4427.2mm, almost 150mm more. This could signify an important change in the local climate that will have implications on the incidence of natural hazards at Arthur's Pass.

It is also worth noting that the average rainfall in the Bealey Valley is significantly lower than the Otira Valley, where many natural hazards exist along the highway, particularly at the site of the Otira Viaduct. In comparison, the yearly average in the upper Otira Valley is as much as 8000mm (Robertson, 1995); a factor that could explain the high rate of erosion and high number of slope instabilities in the Otira Gorge.

2.3.3.3 Snowfall

Because of its high altitude, Arthur's Pass is sometimes a dry, snow-covered landscape during the winter months. Unfortunately, snow records for the township are non-existent and the records that are available from Temple Basin and Bealey Spur (the nearest localities) are incomplete and do not go into detail about specific snow depths or duration.

Information from Bealey Spur (elevation 649m above sea level) refers solely to the incidence of snow (whether it snowed or not, with no snow depth data at all), between 1868 and 1880 (National Institute of Water and Atmospheric Research, 2007). The Arthur's Pass village post-dates this period but it is still a useful set of data for information on historic snow patterns. The records show that it is not uncommon for snow to fall in the summer months at this altitude. The number of permanent snow days each year during 1868 and 1879 averaged 27.

The Temple Basin records are more recent, stretching from 1967 to 1982. The altitude at the Temple Basin ski field is significantly higher than the Arthur's Pass village so the information, whilst relevant, is not directly applicable to the township. The average number of snow days at Temple Basin (elevation 1554m above sea level) is 199 annually.

On 75 of these 199 days, snow fell but melted as it hit the ground, so no snow accumulation was recorded.

Snow avalanches constitute a major hazard, particularly to trampers and skiers in the winter months. Increased snowfall could also impact water volumes within the surrounding catchments once the snow starts to melt in spring and summer. It may also be linked to increasing rainfall, as more atmospheric moisture accommodates the formation of snow.

2.3.4 Vegetation

The variety of plant species observed within the National Park is diverse and noticeably different on either side of the Main Divide. This is attributed to the differences in rainfall between the two regions as this is greatly influenced by the presence of the mountains (Cave, 1987).

The vegetation on the eastern side of the Southern Alps is dominated by mountain beech forests, sub-alpine scrub and montane grasslands, which form a series of separate and quite distinct plant habitats. Odell et al. (1966) reports on several specific plant environments within the National Park boundary and suggests that they are strongly controlled by a number of factors such as altitude, slope gradient, exposure to the elements, soil type and available water resources. The vegetation zones are well defined and obvious to the observer because they are characterised by specific plant types that change as the elevation increases.

The beech forest is the most widespread plant zone surrounding Arthur's Pass, and it contains a very diverse number of plant species. Forested slopes below the tree line are chiefly covered by mountain beech, in combination with several other trees such as broadleaf, ivy, lancewood and celery pine (Burrows, 1977). Smaller shrubs include yellow wood, mapau, stinkwood, snowberry and various ferns and the forest floor is often covered in lichens, mosses and fungi (Odell et al., 1966).

At the base of the valleys amongst the unstable fluvial deposits, the plant life is sparser because it is constantly having to regenerate after the river swells or changes course (Burrows, 1974). The riverbed is dominated by willow herbs and native mat-forming herbs such as scabweed. The stable areas of the riverbed have hardier and more permanent flora such as patotara and some species of everlasting (Odell et al., 1966). Another vegetation zone exists above the tree line where only small shrubs and grasses survive with several species of lichen, moss and native herbs (Parkinson, 2001).

One plant species of note is matagouri, which has several unique qualities that make it a valuable tool for hazard analysis. Matagouri is identified as a resilient shrub with a fast regeneration rate, especially on freshly agitated ground with well-drained soils (Rogers, Walker, & Lee, 2005). It is found in many localities around the village and is particularly useful for recognising disturbances in the soil that may indicate the occurrence of past slope instabilities.

Certain plant species also act to increase the fire hazard, as some native plants are notoriously more flammable than others. Therefore, the distribution and flammability of matagouri and other species of vegetation in Arthur's Pass will be examined and incorporated into the hazard assessment.

2.4 CURRENT AND FUTURE TOWN DEVELOPMENTS

Considering that successful land use planning is one the of the chief methods of mitigation suggested for Arthur's Pass, the location of future developments within the town is of great importance. There is limited vacant space within the Arthur's Pass region that is suitable for further urban development. Although a number of planned developments aim to increase safety by reinforcing structures, building new structures or upgrading old systems, the construction of new buildings within the village area must be weighed against the cost of recovery following natural disaster event. As of late 2007, several developments were either in the process of being built or had been proposed for the village. These include:

1. A $2 million medium-scale construction project centred around the Department of Conservation Visitor Centre, which includes a new public toilet facility to replace the former run-down toilet block, a 16-bay bus park, two carparks and road-widening and landscaping along State Highway 73.
2. The burial of overhead powerlines in zones affected by erosion and flooding as part of the visitor centre development (Selwyn District Council, 2006b).
3. An upgrade of the sewage treatment system that services 14 sections south of Rough Creek. This system was installed when the houses were built along Sunshine Terrace in the 1950's (Selwyn District Council, 2006a). The upgrade will lower the

possibility of environmental contamination and strengthen the septic tank and treatment plant against ground shaking and flooding.

4. The installation of extensive river protection works to protect the railway track through the Bealey Valley and in the Bealey River and Rough Creek to protect parts of the village and transmission line poles. Also, the removal of gravel build-up in some riverbeds adjacent to the township (Department of Conservation, 2007).
5. Proposed road works including the Rough Creek Bridge and road realignment, road widening on State Highway 73 through the Bealey V alley and repair of minor encroachments along the highway (Department of Conservation, 2007).

As for the construction of private dwellings in the village, there is only a limited number of freehold sections available, most of which are already occupied. No more sections would be formed unless there was extreme pressure to make the town bigger. Even then there is nowhere really for the development to go but up the mountains, which is likely to be detrimental to village safety (Costello, 2008).

2.5 PREVIOUS RESEARCH AND THEORY

Hazard research within the Arthur's Pass National Park is extensive, but much of the time it neglects to include any detailed assessments of the more developed areas. Arthur's Pass is the largest settlement in the National Park and contains the highest resident and tourist population in the area, but there is yet to be a detailed investigation of the natural hazards that affect the community.

This section contains an evaluation of previous research theory and methods, paying particular attention to the specific hazards that have been analysed, the effectiveness of research methods and identification of potential areas for further study.

2.5.1 Seismic Hazards

The region is part of a very dynamic tectonic system that has been thoroughly documented since European settlement. Many reports of the seismic hazards along fault lines in the Arthur's Pass National Park have been produced since active fault traces were first identified. Papers by Berryman and Villamor (2004), Cowan (1989), Cowan (1991), Rynn and Scholz (1978), Smith and Berryman (1986), Wells et al (1999), Yang (1991), Yetton

(2000) and Yetton and McCahon (2006) focus on the larger faults, such as the Alpine, Poulter, Kelly and Hope Faults, which are more likely to produce low frequency-high magnitude events that have regional seismic implications for the South Island. Yetton (2000) quantifies the estimated magnitude and intensity and determines return periods for Alpine Fault ruptures.

Arthur's Pass is considered by Rynn and Scholz (1978) to be a zone of tectonic transition between the Alpine Fault (strike-slip movement) and the Hikurangi Trench (subduction movement), where there has been active deformation for the last 2 million years. Attempts to define the deformation associated with earthquakes in Arthur's Pass National Park show some unexpected results. Large earthquake ruptures have previously been interpreted as occurring on faults trending north-east, however, studies by Rynn and Scholz (1978) conclude that the Arthur's Pass region shows a trend of shallow earthquake occurrence in an east-north-east trend, which does not conform to any known fault traces. Furthermore, dislocation models by Arnadottir, Beaven and Pearson (1995) produce a north-north-west trend for the fault associated with the 1994 M 6.7 Arthur's Pass earthquake, and suggest a need for re-evaluation of historical rupture traces in the region.

There is some debate by geoscientists on the existence, location and activity of the Kakapo and Poulter Faults. Yang (1991) identifies the Kakapo Fault as a near-vertical fault much younger in age than the Hope Fault from which it propagates. The Kakapo Fault is further characterised by a dextral displacement of up to 12.1mm/yr and an approximate length of 50km. Cowan (1989) suggests that in a comparison between the Hope Fault and Kakapo Fault, the Kakapo Fault is much less active and there is a lack of rupture data to make any accurate conclusions about the risk it poses. Berryman and Villamor (2004) investigate the Kakapo Fault and fail to find any evidence for recent seismic activity along the trace proposed by Yang (1991). They redefine the fault trace as the Poulter Fault and credit it with generating the 1929 M 7.1 Arthur's Pass earthquake.

Smaller localised fault traces typically generate high frequency-low magnitude events but they are equally important for seismic hazard studies at Arthur's Pass. There is a lack of comprehensive information relating to these faults, but several are highlighted by Chamberlain (1996) and include the Red Rock Fault Zone, Punchbowl Fault Zone, Scott Fault and the Aicken O'Malley Fault. The Arthur's Pass township is essentially at the confluence of two major fault zones; the Alpine Fault and the Marlborough Fault zone

(Smith & Berryman, 1986) which has produced a complex seismic zone with many unnamed and possibly unidentified faults that have the potential to generate earthquakes. Compared to towns sited on the Canterbury Plains, Arthur's Pass is twice as likely to experience ground shaking because the seismic risk increases westwards from Christchurch (Soils and Foundations Ltd, 1993). Therefore, in the event of a major earthquake, the village is likely to be severely damaged because it lies at the centre of a very seismically active region (Rynn & Scholz, 1978).

Some of the seismic research available focuses on specific earthquake events and describes the condition of the physical environment and the societal impacts that resulted from each earthquake. Arnadottir et al (1995), Berrill et al (1995), Chamberlain (1996), Cowan (1991), McSaveney (1982a), Paterson and Berrill (1995) and Speight (1933) offer examples of such reports. Speight (1933) was the first to report on the effects of the 1929 M 7.1 Arthur's Pass earthquake in which he identified fresh scarps and cracks in the nearby mountains. There were fairly high social implications resulting from the 1929 event because it caused a high degree of damage and the road was closed for months afterwards (McSaveney, 1982a). The 1994 M 6.7 Arthur's Pass was one of the best-documented seismic events in the region and enabled geoscientists to study the complex fault system that caused the earthquake. Arnadottir et al (1995) used the earthquake as a case-study to model the coseismic displacements and subsequent location of the active fault trace.

2.5.2 Mass movement hazards

Studies undertaken within the National Park highlight the numerous mass movement events that have occurred sporadically over the last 140 years. The vast majority of research targets the geomorphic hazards that have led to temporary road closures along the highway, with limited detail given to slope instabilities that could directly affect the village. Owens et al (1994) group mass movements into three classes; rainfall-triggered failures, earthquake-generated failures and other types of failures such as ground subsidence.

Whitehouse and McSaveney (1992) and Paterson (1996) assess slope stability along the highway corridor, specifically targeting the vulnerability of slopes to rockfalls, rock avalanches and debris flows. Drainage channels immediately south of the Arthur's Pass village are recognised as being highly susceptible to debris flows, particularly during periods of heavy rainfall (Paterson, 1996). Debris fans deposited by Grahams Creek, Rough Creek and Wardens Creek pose the biggest threat to infrastructure in the village (E. Smith, 2004) but smaller rockfalls are typically the most common hazard and regularly impair the road (McSaveney, 1982b).

Earthquake-generated mass movements have been thoroughly documented by Hancox et al (1997), Keefer (1984), Owens et al (1994) and Whitehouse and Griffiths (1983). Keefer (1984) concludes that failures are more likely to occur in highly weathered or fractured rocks that are affected by active river erosion. The impacts that slope gradient and vegetation have on slope stability are also crucial factors in determining the level of risk that landslides and rock avalanches pose in the National Park (Cave, 1987).

Several large earthquake-generated movements have occurred in the National Park, most predominantly in the Otira Gorge but occasionally within the vicinity of the Arthur's Pass township. A narrow zone of earthquake-induced landslides was produced during the 1929 Arthur's Pass earthquake and identified by Speight (1933). It was later used by Berryman and Villamor (2004) to identify the fault segment that ruptured during the earthquake. They also analysed the rock avalanche deposits from Falling Mountain and reconstructed the sequence of events and conditions that led to such a major slope failure.

Various engineering solutions have been employed to restrict the amount of damage mass movements can do within the National Park, particularly to infrastructure. Directly north of the township, road cuts have been strengthened to better cope with hazardous conditions (E. Smith, 2004). The Otira Viaduct and rock shelter are possibly the best example of a long-term mitigation solution to major mass movements. Bridges within the National Park and the Otira Gorge have been reinforced to withstand large forces from both earthquakes and sediment transport (Berrill et al., 1995). Within the township, minimal research has been conducted on ways of managing slope failure hazards, which is a key component of the present research.

2.5.3 Meteorological hazards

The most prominent meteorological hazards to affect the village are storms, snow avalanches and climate change, which has implications for weather processes.

Meteorological factors tend to act as a trigger for other hazards, such as mass movements or erosion (Kovach & McGuire, 2003).

Storms occur in Arthur’s Pass several times a year and typically generate high rainfall, hailstorms and wind gusts, but most of the time no damage is caused (Odell et al., 1966). A major storm event occurred in December 1957, when high rainfall at Otira and Arthur’s Pass generated flooding, river aggradation, debris flows and landslides (Whitehouse & McSaveney, 1992). Footbridges crossing the Bealey River were washed away and the road was temporarily closed (McSaveney, 1982b).

An account of the December 1979 storm was given by Cave (1979a). The storm produced very heavy and prolonged periods of rain over two days, which resulted in damage to the highway from washouts and gravel deposition. The drainage systems were unable to cope and became blocked and washed out, which increased the flooding along the highway and within the village (Cave, 1979a). Bridge abutments were compromised when the excess water flow concentrated around them and produced small washouts. The rain also triggered small mass movements along an extended stretch of State Highway 73. It is not apparent what, if any, hazard control measures were implemented after these storm events that could have reduced the risk in subsequent storms.

Snow avalanches are a common occurrence in the winter months. Although they do not appear to be a direct threat to the township, they do occur in the Bealey Valley (Department of Conservation, 2007). Waters (1980) infers that the snow avalanche hazard is concentrated in the vicinity of the Temple Basin Ski Field and along major tramping routes that are used throughout the winter months. The Department of Conservation (2007) lists Avalanche Peak (forming part of the Avalanche Path), the Bealey Valley near the Bealey Glacier and Rough Creek as extreme risk areas. In the case of Rough Creek, wet snow avalanches have the potential to travel all the way to the creek bed, with flattened vegetation being the identifying factor of such an event (SoftRock NZ, 2008b). Since 1926, 12 people have died in avalanche related incidents in the Arthur’s Pass National Park (Kates, 2008). There is currently some debate over avalanche control methods, especially in Canterbury ski fields where the terrain is particularly dangerous and unpredictable (Owens et al., 1994). The degree of risk associated with an avalanche is dependent on the magnitude and frequency at each avalanche site, because each locality varies considerably.

Site specific investigation on terrain controls and severity is necessary for an accurate avalanche hazard assessment (Waters, 1980).

Studies on local climate change are non-existent, which highlights a need for further examination. Records of rainfall and temperature do show a slight trend that will be investigated as part of this hazard assessment.

2.5.4 Flooding hazards, erosion and sedimentation

Past research is typically limited to factual accounts of storm damage and brief inspections of changes to the local landscape. It is apparent from the numerous accounts of storm events that sizeable floods occur every few years at Arthur's Pass. In an analysis of local geomorphic change, McSaveney (1982b) records several historical floods that have been significant to the Arthur's Pass village. The storm in 1957 generated flooding that destroyed almost all the footbridges in the Arthur's Pass National Park and damaged the railway line and roads in both the Bealey and Otira Valleys (McSaveney, 1982b). Railway embankments were washed away and numerous incidents of aggradation were reported. The December 1979 storm had a similar effect, causing widespread damage and weakening nearby slopes and riverbanks (Cave, 1979a). In addition to flooding, sedimentation and erosional processes have been identified in almost all cases of storm damage at Arthur's Pass.

Whitehouse and McSaveney (1992) discuss several ways in which flooding can occur that provide a valuable insight into potential methods of management. Common causes of flooding in Arthur's Pass are blocked drains and culverts that are not able to cope with high water flow. Natural floods typically initiate when river banks breach or overtop and when low lying areas become inundated during periods of high rainfall (Owens et al., 1994). The town is at risk of being affected by flooding because of its close proximity to the Bealey River. The river also has a high erosive capacity and the ability to deposit substantial amounts of sediment into the system which has the potential to seriously affect the town infrastructure (E. Smith, 2004).

McSaveney (1982b) highlights the importance of precipitation as a major control on erosional processes. The extent to which rainfall influences erosion is variable, but Whitehouse and McSaveney (1992) note that scouring often has the potential to induce slope failures in the National Park, which is an important consideration in this hazard assessment.

2.6 RESEARCH PRACTICE METHODS

Several approaches have been used in previous hazard assessments. An in depth knowledge of the field area is imperative. Past research has been completed using aerial photography coupled with ground reconnaissance and in-field mapping. Much of the literature contains first-hand observations of the hazards and the impacts they have on both man-made and natural features.

Several researchers use both deterministic and probabilistic models to study the behaviour of earthquakes, climate, rivers and slopes to facilitate the prediction of future hazards. In order to determine frequency and predict the magnitude of future events, records of past events are vital. Almost all the previous research conducted on natural hazards has included information derived from historical data.

Many of the reports identify the importance of an effective hazard response in reducing the risk to the community. The main objective of any hazard assessment is to identify risks. Once recognised, the threats to the community can be reduced by implementing successful mitigation measures and a employing a well-organised emergency plan.

CHAPTER 3
SEISMIC HAZARDS

3.1 INTRODUCTION

This chapter is the first of four specific hazard assessment chapters. Earthquakes are a "driving" force and are responsible for the initiation of a number of other natural hazard events. They also differ from other hazards in that they are not restricted a specific location. The earthquake risk at Arthur's Pass is high. In addition to several recognised faults, the complex fault zones surrounding Arthur's Pass almost certainly contain many unidentified faults which contribute to the seismic risk. Prior knowledge of fault behaviour and an understanding of the mechanisms that drive fault movement are key aspects in this earthquake hazard evaluation.

The objectives of the seismic hazard analysis are:

1. To analyse the seismicity of the Arthur's Pass region for the purpose of identifying as many faults as possible.
2. To determine the level of risk that the faults present both individually and collectively.
3. To discuss previous earthquakes that have affected the Arthur's Pass region in recorded history.
4. To conduct a seismic hazard evaluation, examining the classification of seismic hazards at Arthur's Pass.
5. To discuss the implications of both regional and local earthquakes in terms of the risk to people, property and essential infrastructure and access to external support following a disaster.
6. To evaluate the current mitigation methods at Arthur's Pass for earthquake hazards

3.2 ANALYTICAL TECHNIQUES

This seismic hazard assessment combines several approaches. Detection of fault traces using aerial photographs is a method through which high risk areas have been identified. For this analysis, aerial photographs from 1938, 1943, 1960, 1977, 1998 and Google Earth satellite images from 2007 have been used to compare changes in the geomorphic landscape and monitor specific areas that are deemed to be high risk from a hazard perspective over the last 80 years.

Integrating historical data with scientific knowledge is essential because it forms the basis for probabilistic seismic hazard models and gives an indication of future rupture locations. Seismicity is a combination of both space and time elements; the historical data make up the time component and the fault distribution forms the space component. The approximate size and extent of fault traces is inferred through the investigation of past ruptures. Therefore, fault locations and past earthquake occurrences have been analysed in order to gauge the seismicity of the Arthur’s Pass region and assist in the future prediction of tremors in the region.

An in depth fault analysis has not been carried out in the field; most of the information has been collected from independent sources such as government reports, fault databases, journal articles, aerial photos and personal accounts of earthquake events from witnesses. Owing to the nature of the terrain around Arthur’s Pass, field reconnaissance is difficult and fault traces often go unnoticed in dense bush, but every attempt has been made to include all possible faults and integrate them into the overall seismic hazard.

3.3 SEISMICITY AT ARTHUR’S PASS

The processes that shaped New Zealand approximately 250 million years ago are also responsible for the formation of the Southern Alps. Periods of continental collision between the Australian and Pacific Plates have accommodated mountain-building processes and produced the high structural complexity that is observed today.

Earthquakes at Arthur’s Pass are caused by sudden stress changes along subsurface faults that result in ground shaking and occasional rupture at the Earth’s surface. Ground shaking is measured using the Modified Mercalli (MM) Intensity Scale (Appendix B). Seismicity is a measure of earthquake activity using both the spatial and historical distribution of earthquakes throughout Canterbury and also the South Island.

Arthur’s Pass is located at the oblique confluence of Alpine Fault and Marlborough Fault Zone (Figure 3.1). As a result, the seismicity of the Arthur’s Pass region reflects the seismic traits of both fault systems. There is an unquestionable pattern of seismicity when comparing the proportion and distribution of deep (>40km) and shallow (<40km) earthquakes in the New Zealand (Figure 3.2). Most noticeable is the absence of deep earthquakes along a section of the Alpine Fault in the central South Island (Institute of Geological and Nuclear Sciences Ltd, 2000). This absence can be attributed to the different tectonic mechanisms operating along the collisional boundary and represents the translation of the northern subduction zone into the southern strike-slip fault zone as the Australian Plate meets the Pacific Plate (Coates & Cox, 2002).

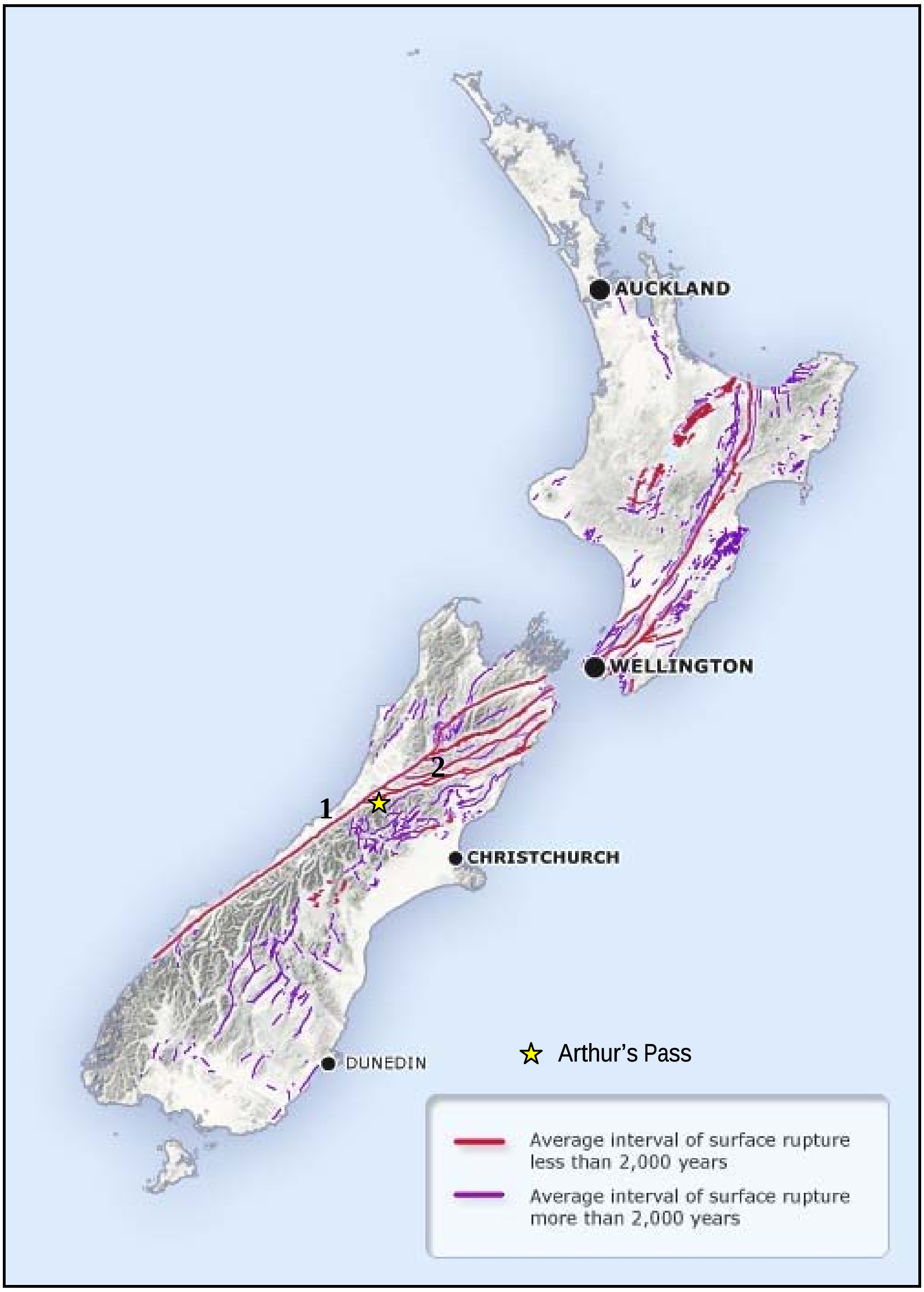

Figure 3. 1. New Zealand's active onshore faults, showing Arthur's Pass at the confluence of the Alpine Fault (1) and the Marlborough Fault System (2) (McSaveney, 2007).

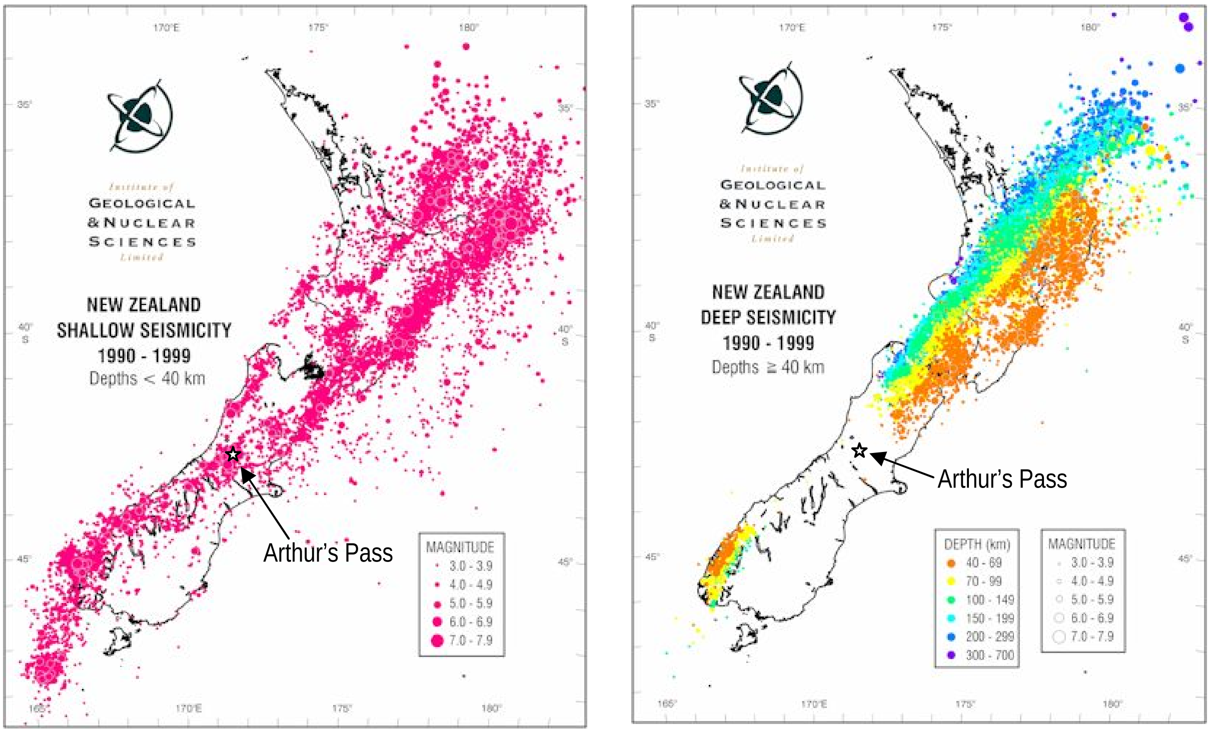

Figure 3. 2. Distributions of shallow and deep earthquakes for the period 1990-1999, showing the absence of deep tremors in the central South Island (Institute of Geological and Nuclear Sciences Ltd, 2000).

In New Zealand, the pattern of earthquake activity does not correspond well to the surface geology (Smith & Berryman, 1986), so it is a complicated task to get a complete representation of the local seismicity simply through field observations and aerial photo analysis. Previous investigations on specific fault locations have been used to determine where faults exist and how active they are, as a detailed in-field investigation of fault occurrence is considered beyond the scope of this project.

Earthquake monitoring stations (GeoNet) around the South Island record hundreds of microearthquakes in the region that characterize zones of activity. The dense spatial distribution of shallow earthquakes in the Arthur's Pass region (Figure 3.3) suggests that the majority of earthquakes tend to be associated with zones of crustal weakness (Rynn & Scholz, 1978). The bulk of earthquakes are in the seismogenic zone and show an inverse hazard relationship; the shallower the earthquake, the greater the hazard (Bell, 1999). There is no shortage of historical earthquakes that provide data for future calculations of earthquake occurrence. There are, however, limits as to how much of the data can be used for the purpose of accurately forecasting earthquakes, especially because there is very little information on slip rates and recurrence intervals.

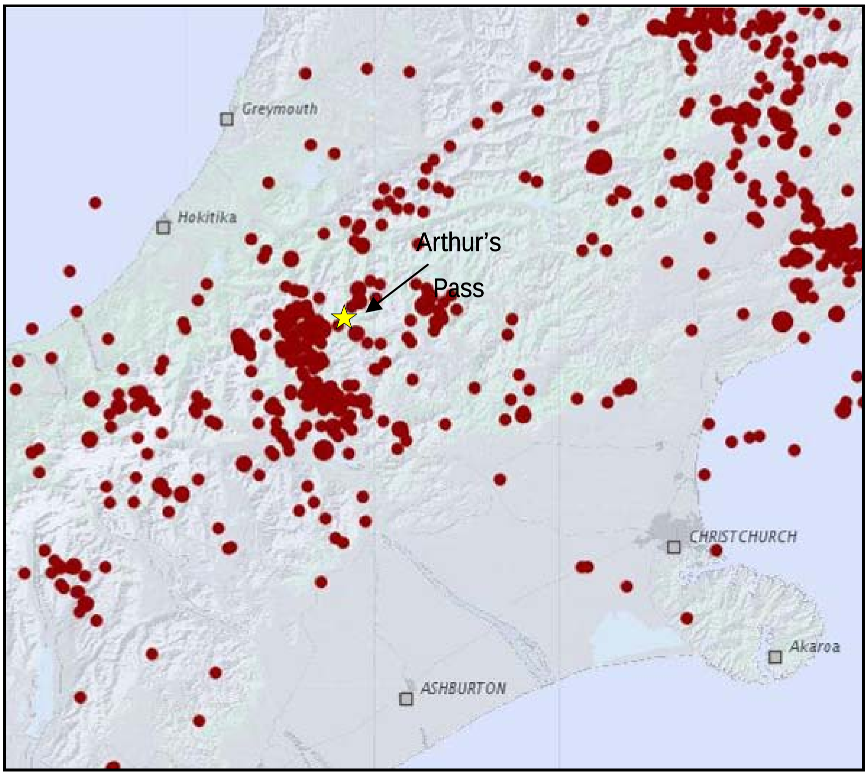

Figure 3. 3. Spatial distribution of shallow earthquakes (<40km depth) over M 5 in recorded history in the Arthur's Pass region, which may be linked to zones of crustal weakness (Institute of Geological and Nuclear Sciences Ltd, 2008b).

Rynn and Scholz (1978) hypothesised that the Arthur's Pass region is in fact part of a developing shear zone because no surface ruptures had been found to prove otherwise. Subsequent examination of the faults responsible for the most recent earthquakes may suggest that surface expression does exist in the Arthur's Pass region and most of the plate deformation is accommodated by left-lateral movement along cross-faults to the north-east and south-west of Arthur's Pass village (Arnadottir et al., 1995).

The high seismicity at Arthur's Pass can explain why mean return periods for earthquakes that produce high intensity ground shaking in the region are short compared to other locations in the South Island. Based on information from Paterson (1996) and Smith (1990), the areas with the most frequent high-intensity earthquakes are Nelson and Westport, closely followed by Arthur's Pass and Otira (Table 3.1).

LOCATION	EARTHQUAKE INTENSITY (MM)			
	IV	*VII*	*VIII*	*IX*
Nelson	5	16	56	200
Westport	8	26	91	330
Arthur's Pass/Otira	9	31	100	370
Mt. Cook	14	48	170	475
Queenstown	12	54	250	1100
Milford Sound	12	62	330	1800

Table 3. 1. The mean return periods at various locations for selected ground shaking intensities (Adapted from (Geotech Consulting, 1998; Paterson, 1996; Stirling et al., 2007; West Coast Regional Council & DTec Consulting, 2002).

The updated probabilistic seismic hazard assessment for the Canterbury region (Stirling et al., 2007) makes note of the fact that most earthquakes greater than M 6.5 occur along faults that are not represented in surface features and are therefore often go unnoticed by researchers. The lack of surface ruptures makes it necessary to rely on historical earthquakes and fault data (Chamberlain, 1996). There is also potential for large earthquakes to occur in the future along unrecognised faults. This theory is based on the incidence of historic tremors over M 6.5 that have yet to be assigned to specific fault lines.

Hazard estimate maps generated from the probabilistic seismic hazard assessment indicate that the hazards have very different seismic patterns across the whole of Canterbury. The Arthur's Pass region has been acknowledged by the report as the region most likely to experience the highest ground accelerations and shaking intensity because of its location close to several major plate boundary faults. It has been projected that Arthur's Pass will encounter very high shaking intensities that increase as the recurrence interval increases (Table 3.2) (Appendix C).

Recurrence Interval (years)	Shaking Intensity (MM)
31-50	VI-VII
100-150	VIII-IX
150-475	IX-X
1000+	IX-X

Table 3. 2. Projected shaking intensities (Modified Mercalli Intensity Scale) and corresponding return intervals for Arthur's Pass (Stirling et al., 2007).

Deterministic methods of earthquake prediction employ the use of field observations and can help to improve statistical prediction. However, New Zealand historical records are limited to 150 years, which is only useful for gauging the short-term risk (K. Smith, 2004). Unlike other hazards such as debris flows and tsunami, accurately forecasting earthquakes is essentially impossible and does not allow for pre-emptive warnings to be issued.

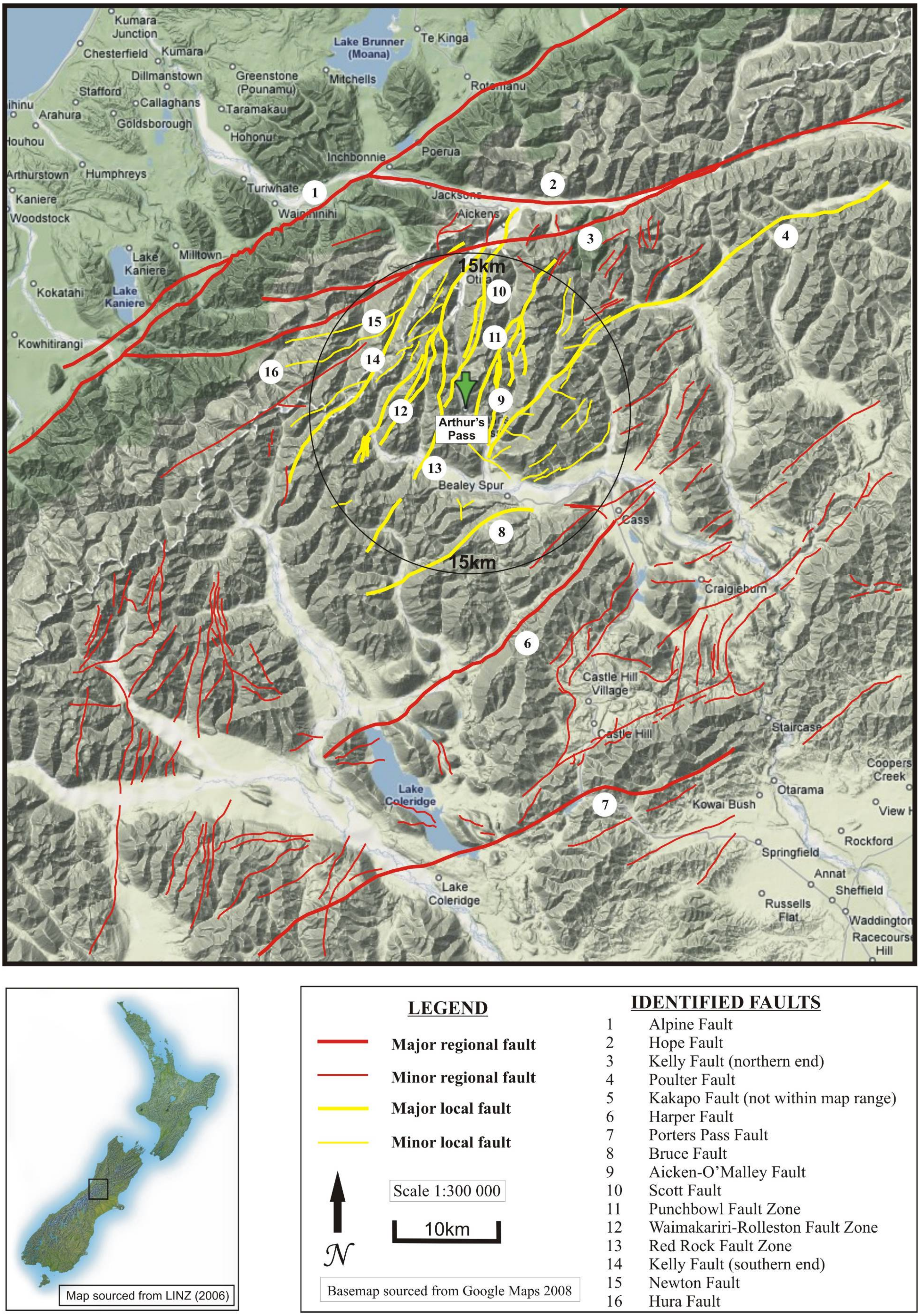

Figure 3. 4. Faults in the Arthur's Pass region that contribute to the overall seismic risk. Faults within a 15km radius are considered to be local fault sources, whilst those outside a 15km radius are regional fault sources (fault data from (Cave, 1987; Chamberlain, 1996; Environment Canterbury, 2007; Institute of Geological and Nuclear Sciences Ltd, 2008a)).

3.4 FAULTS IN THE ARTHUR'S PASS REGION

Several large-scale faults and countless minor faults exist in the South Island of New Zealand that contribute to the seismic risk at Arthur's Pass (Figure 3.4).

The Alpine Fault is characterised by long periods of quiescence punctuated by periodic, high-magnitude earthquakes. Conversely, the Marlborough Fault Zone is continuously producing moderate levels of seismic activity in addition to large, infrequent tremors (Rynn & Scholz, 1978). Active faults within roughly 50km of the village are expected to be the greatest threat to the township in terms of earthquake hazards.

Initial observations in the Arthur's Pass region indicate there is an underlying trend of predominant fault orientation in a north-east direction. The majority of faults have a dextral strike-slip movement and the few thrust faults that exist typically dip south-eastwards (Chamberlain, 1996). Cross-faulting is evident in the region and there is potential for a single fault rupture to initiate rupture in other adjacent faults, compounding the seismic hazard.

By studying the location of faults, it is possible to constrain the spatial distributions of earthquakes and thus have the first component towards understanding the seismicity of the Arthur's Pass area. A distinction has made between regional and local seismic sources because they create different earthquake scenarios.

3.4.1 Regional faults

Faults propagating more than 15km from the Arthur's Pass village are considered for the purposes of this study to be regional faults. They are often larger, well-defined faults that have been investigated previously. The major regional faults are associated with substantial displacements during high magnitude, long-duration earthquakes and are expected to cause high levels of ground shaking across an extensive area within the South Island.

3.4.1.1 The Alpine Fault

The most significant regional fault generating a high seismic risk is the Alpine Fault; a 650km long dextral strike-slip fault north west of Arthur's Pass with lateral movement of approximately 22-30mm/yr and an estimated uplift of 7-10mm/yr in the central fault segment (Yetton, 2000). Return periods for the Alpine Fault vary widely for two reasons; there has never been a recorded Alpine Fault rupture in recorded history, and only three past events are represented in palaeoseismic data. Estimates put the probability of a major fault rupture along the Alpine Fault at 65 ±15% over the next 50 years and as much as 85 ±10% in the next 100 years (Yetton, 2000).

Calculations of the timing of the last two Alpine Fault earthquakes in 1620 AD and 1717 AD have been obtained using tree-ring chronologies, trenching methods and landslide debris dating. Computer-modelled isoseismal maps from the two previous ruptures show Arthur's Pass in the region with the highest shaking intensities (estimated at MM IX+) during both earthquakes (Downes & Institute of Geological & Nuclear Sciences Limited., 1995) (Figures 3.5A and 3.5B). Through the reconstruction of these past events it is evident that the next Alpine Fault rupture will be sizeable as well. The earthquake magnitude is likely to be M 8+ and ground shaking near the rupture zone will reflect that of the last two earthquakes. Arthur's Pass will be in the zone of highest ground shaking with approximately MM IX (Smith, 1990) in (Yetton, Wells, Traylen, New Zealand Earthquake Commission., & Geotech Consulting, 1998).

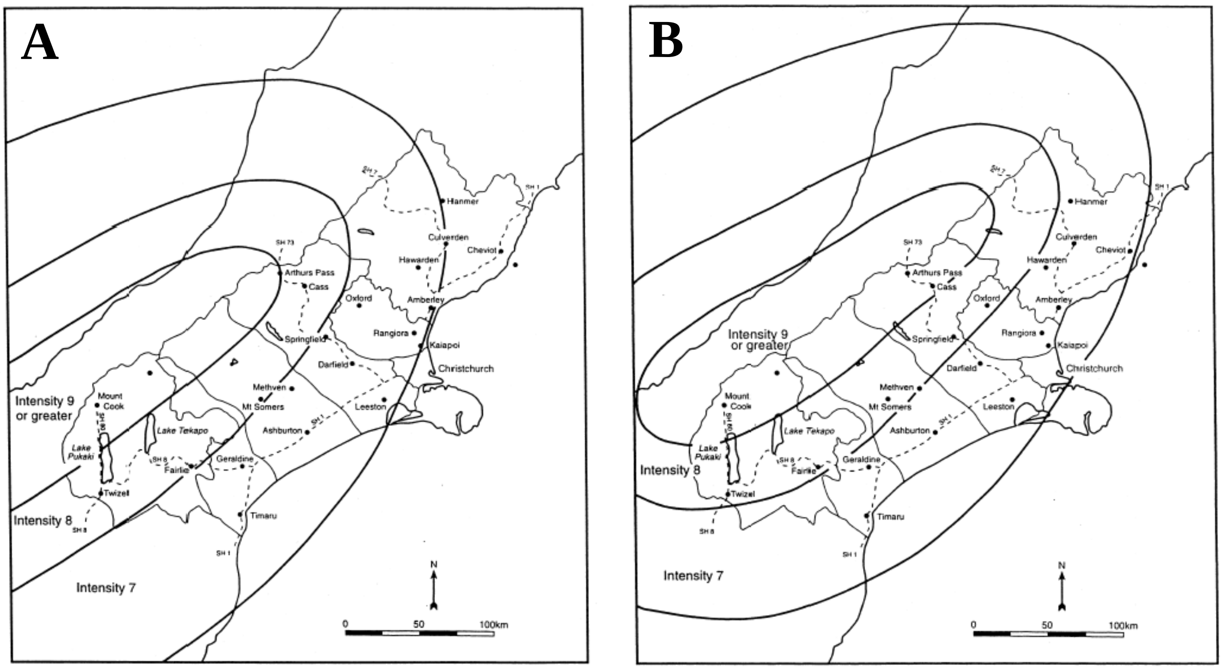

Figure 3. 5. Computer-modelled isoseismal maps of past Alpine Fault earthquakes. **A.** The 1620 AD earthquake showing Arthur's Pass in the zone of highest ground shaking intensity. **B.** The 1717 AD earthquake showing Arthur's Pass on the edge of the zone of highest ground shaking intensity ((Smith, 1990) in (Yetton et al., 1998)).

3.4.1.2 The Marlborough Fault System

The Hope Fault represents the southern section of the highly segmented Marlborough Fault Zone. It accommodates large amounts of deformation and stress from the transfer of the plate margins across the South Island (Pettinga, Yetton, Van Dissen, & Downes, 2001). The Kelly Fault propagates from the Hurunui section of the Hope Fault, forming a zone of seismicity 42km long. The southern section of this fault has been included as a major local fault. The Kelly Fault has been recognised as the most likely source of a major earthquake at Arthur's Pass for the 475 year return period (Stirling et al., 2007) and the junction of the Kelly and Hope Faults is a particularly dynamic region for shallow earthquake activity (Rynn & Scholz, 1978). This section of the Marlborough Fault System has an interpreted slip rate of 11.5-14.5mm/yr and an average recurrence interval of 310 to 490 years (Yetton & McCahon, 2006). Future ruptures along the Hope Fault may produce earthquakes with magnitudes up to approximately M 7.4.

Associated with the Hope Fault are the Kakapo and Poulter Faults. The Poulter Fault is a newly recognised dextral strike-slip fault extending almost 50km west-north-west, sub-parallel to the Alpine Fault with an average slip rate of 1mm/yr (Berryman & Villamor, 2004) and an extended return period of between 3500 and 5000 years (Stirling et al., 2007). It has been included as a local source on the fault map (Figure 3.4) because the southern section of the fault comes within close proximity to the village area.

The Kakapo Fault is a young, 50km long fault that propagates from the Hope Fault. Return periods and slip rates for the Kakapo Fault are poorly understood, but assessments undertaken by Yang (1991) suggest an average dextral displacement of 6-6.8mm/yr. This has been disputed by Berryman and Villamor (2004) who cannot find any evidence for active dextral movement along the western division of the Kakapo Fault.

3.4.1.3 Other regional faults

There are currently no palaeoseismic data to support any Holocene activity along the Harper Fault although it does represent a potential earthquake source because of the deep aftershock activity it produced as a result of the 1994 Arthur's Pass earthquake (Yetton & McCahon, 2006). It is characterised by a 49km-long thrust fault dipping towards the south-east near Lake Coleridge.

The Porters Pass-Amberley Fault Zone propagates north-east along the base of the Southern Alps where the foothills meet the Canterbury Plains. Palaeoseismic data point to several previous large-scale earthquakes within this highly segmented fault zone during the Holocene. Slip rates have been difficult to verify but they are estimated at between 0.5 and 5mm/yr (Pettinga et al., 2001). The Porters Pass Fault forms the eastern section of the fault system and probably has the most significant implications for Arthur’s Pass. It is characterised by a 40km-long discontinuous surface trace with average slip rates of 3.2-4.1mm/yr and an estimated recurrence interval of 1500 years (Yetton & McCahon, 2006). It contains numerous small branches and displays juvenile behaviour. Previous attempts to determine whether the fault zone produces recurrent, small size earthquakes or infrequent large tremors to account for the displacement along the fault have been inconclusive.

It is assumed that all large-scale regional faults affecting Arthur’s Pass have already been identified in earlier investigations. They constitute a prominent threat over Canterbury and Westland and throughout the South Island and therefore a certain level of preparedness is required because they represent such a widespread risk.

3.4.2 Local earthquake sources

Local faults are classified as less than 15km from the township centre. They include a large number of unnamed or unidentified faults, plus several recognised faults. Local faults are not likely to induce excessive ground shaking across an extensive area; populated centres close to the epicentre are likely be the only localities affected. Information collected from the Institute of Geological and Nuclear Sciences (GNS) Active Faults database and from the records of Environment Canterbury have assisted greatly in constructing fault maps showing as many potential seismic sources as possible. There are several recognised local faults propagating through the Arthur’s Pass region (Table 3.3).

Fault Name	Fault Sense	Orientation	Dip angle and direction
Bruce Fault	Dextral	NE	Unknown
Aicken-O’Malley Fault	Unknown	NNE	Unknown
Scott Fault	Unknown	N to NE	Unknown
Punchbowl Fault Zone	Dextral	NNE	70-90°, west
Waimakariri-Rolleston Fault Zone	Reverse and sinistral	NE	80-90°, west
Red Rock Fault Zone	Reverse	N to NE	45-70°, west
Kelly Fault (southern end)	Dextral	NE	Unknown
Newton Fault	Dextral	ENE	Unknown
Hura Fault	Dextral	ENE	Unknown

Table 3. 3. The recognised local faults at Arthur’s Pass (Cave, 1982; Chamberlain, 1996).

The Bruce Fault, which lies to the south of Arthur's Pass, is one of the larger and more extensive fault traces within the local source classification. The Scott Fault, Punchbowl Fault Zone and Red Rock Fault Zone come to within very close proximity of the village itself. The Waimakariri-Rolleston Fault Zone propagates throughout the area defined by Mt. Rolleston to the east and similarly the Aicken-O'Malley Fault is splayed throughout the Mt. Aicken and Mt. Franklin area to the west of the village. The Newton Fault and Hura Fault may also be of seismic significance to the Arthur's Pass village given their location near the southern segment of the Kelly Fault, close to the Alpine Fault. The majority of local faults are dextral strike-slip faults. There is no evidence of thrusting along any of the faults mentioned above.

Adding to the complexity of the local tectonic landscape is a series of faults forming a complex north-south shear zone approximately 750m upstream of the Rough Creek river mouth identified by Cave (1982). Due to lack of surface evidence, fault movement could not be established but the north-east oriented faults are thought to postdate all other faults in the area.

Specific data on slip rates, return periods, average displacements per event and elapsed time since the last event are widely unknown for these faults. Consequently, it is not possible to employ the probability models to determine the probabilistic risk that exists from local sources in this instance. The increasing number of known local faults implies that there are still many unknown local faults that have an unlimited capacity to generate earthquakes. There will always be a constant background risk of unknown probability associated with the faults around Arthur's Pass, so preparedness rather than prevention is the best form of mitigation.

3.5 HISTORICAL EARTHQUAKES

Past earthquakes that have affected Arthur's Pass constitute the second component of the seismicity study. The historical distribution of earthquakes is an important consideration when predicting the possible time and location of future fault ruptures because they provide information on fault positions, recurrence intervals and future magnitudes.

There are limitations to using historical data for probability models because the earthquake information in New Zealand is no more than 150 years old. Many of the larger regional faults have a return period longer than 200 years, so the historical data are not a totally true representation of the seismic activity in the country. The earthquakes discussed below represent those that had a high enough magnitude to cause damage close to the Arthur's Pass township (Figure 3.6). There is some conflict in the literature on specific magnitudes for several earthquake events. For continuity purposes all magnitudes have been taken from the GNS Active Faults Database (2008a).

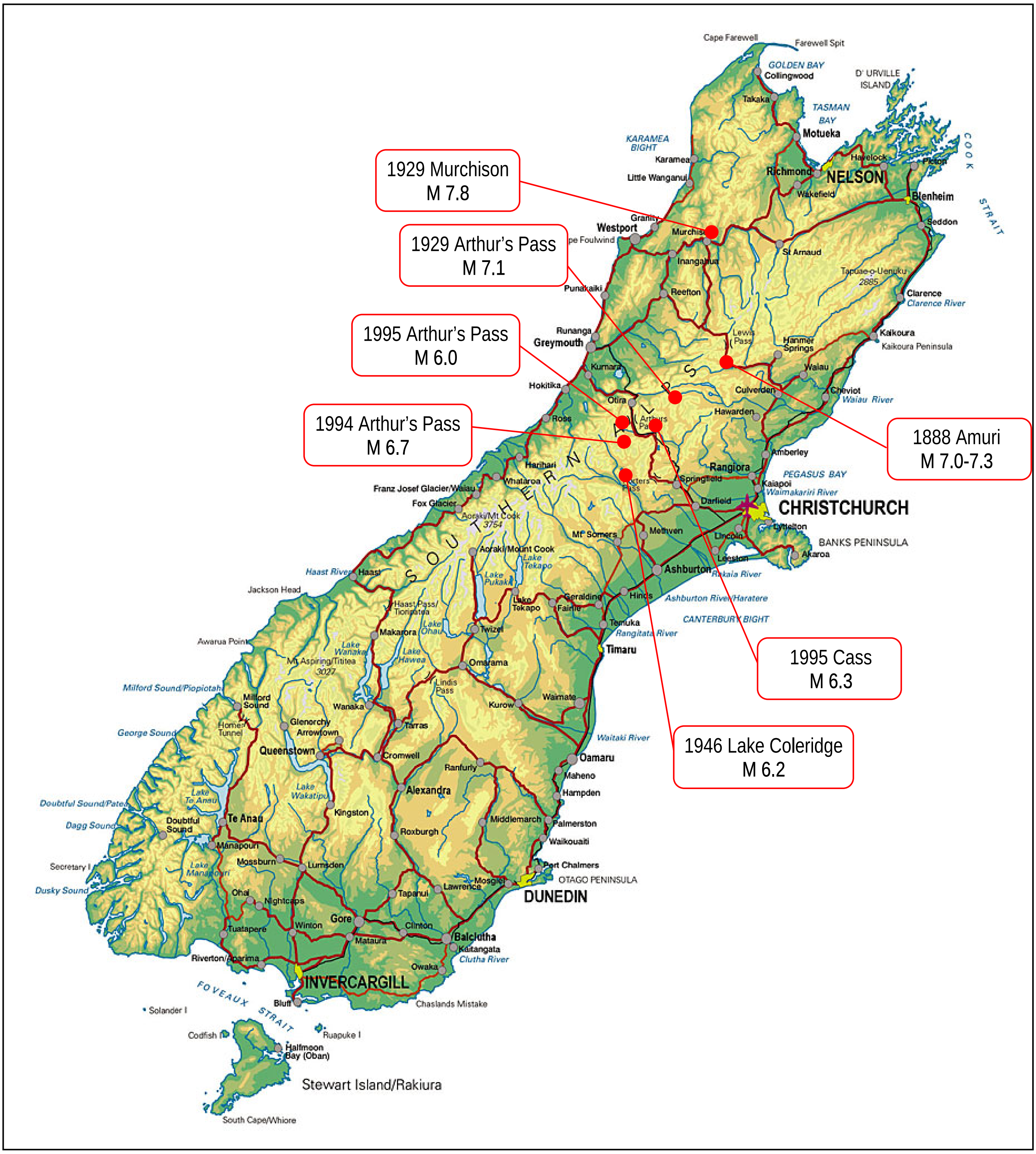

Figure 3. 6. The locations of seven major earthquakes to have affected Arthur's Pass in recorded history (map courtesy of (New Zealand Tour Maps, 2008)).

3.5.1 The September 1, 1888 Amuri (North Canterbury) earthquake (M 7.0-7.3)

The largest earthquake ever to occur in Canterbury was the 1888 Amuri earthquake that ruptured along the Hope River Segment of the Hope Fault associated with the Kakapo Fault near the Hanmer Plains (Berryman & Villamor, 2004). Cowan (1989) estimated the magnitude at 6.5-6.8 but it was later expressed by Yetton and McCahon (Yetton & McCahon, 2006) as 7.0-7.3. The village at Arthur’s Pass had not yet been established in 1888 but intensities reached MM VII-VIII at the village site (Figure 3.7A) and the road sustained considerable damage from landslides and small rockfalls that closed the road for several days (Cowan, 1989).

3.5.2 The March 9, 1929 Arthur’s Pass earthquake (M 7.1)

The Arthur’s Pass earthquake is the largest recorded earthquake in Selwyn District since European settlement (Yetton & McCahon, 2006). It was felt throughout the South Island. The ground shaking intensity was estimated at MM IX at Arthur’s Pass (Figure 3.7B), and damage was quite extensive throughout the town. A previous investigation by Yang (1991) suggested that the cause was a fault rupture along the Kakapo Fault. This was later dispelled by Berryman and Villamor (2004) who concluded that it in fact occurred along the newly identified Poulter Fault, at an epicentre approximately 34km north-east of Arthur’s Pass village, with a focal depth of 11km.

The earthquake occurred at night when most of the community were at a social dance in a building that sustained only minor damage and consequently, no deaths were reported. The duration of the shaking was over four minutes, which was enough to cause people to lose their footing and for furniture and home contents to be shifted considerable distances(Yetton & McCahon, 2006). The aftershocks began almost immediately after the main event and they continued for several weeks after the initial earthquake (McSaveney, 1982a).

The earthquake caused critical structural damage to houses, loss of power to the township and generated a state of panic amongst the residents. Other damage included collapsed brick chimneys and burst water pipes (Yetton & McCahon, 2006). The railway line was warped and broken and the signal wiring damaged. Cracks appeared in concrete at the yard and a 1.5km long fissure followed the railway line towards the pass. However, within two days, the railway line had been repaired and the train schedule resumed as normal (McSaveney, 1982a). The road was severely damaged by rock debris and in several places was completely buried or rigorously cracked. Approximately 1km south of the village, the road had been removed by a large rock slide, and numerous oversized boulders had fallen from the steep slopes and dented the road (Yetton & McCahon, 2006). Repairs to the road took several months before it was reopened, and included restoration of a substantially damaged section of highway in the Otira Gorge.

All the bridges leading to Christchurch survived but most sustained ground subsidence at the base of their abutments and were unapproachable. The Otira tunnel remained intact and the only related damage was some cracks found in the railway embankments at the Otira end of the tunnel entry (McSaveney, 1982a).

Further investigation of the landscape uncovered a number of landslides and rockfalls in the surrounding hills, which continued for up to four years after the initial earthquake (Pettinga et al., 2001). Possibly the most significant of these was the Falling Mountain rock avalanche in which 60 million cubic metres of greywacke rock sheared off a 900m ridge into the Otehake River valley (SoftRock NZ, 2008b). Speight (1933) was the first to document the scientific implications of the earthquake, in which he identified a narrow belt of approximately 40km long by 4km wide within the National Park that showed an intensified susceptibility to landslides and rock instabilities compared to the surrounding areas. To account for this anomalous landslide distribution, it was suggested by Berryman and Villamor (2004) that this zone represented the locality of the fault trace, which is estimated at 16-36km long. This is further substantiated by fresh scarps that were identified in this landslide zone that contradict the Kakapo Fault trace proposed by Yang (1991), along which no active fault rupture could be found (Berryman & Villamor, 2004).

Other geomorphic changes included the appearance of huge dislodged boulders that travelled down the slopes to rest behind many of the houses. They can still be observed on School Terrace amongst the hostel buildings. The Devil’s Punchbowl Falls were dramatically transformed when the earthquake caused the front rock face to shear off, which deposited large amounts of debris into the rock pools below. There was also a minor slip nearby that choked the stream and forced the water to travel through the debris to reach the Bealey River (McSaveney, 1982b).

3.5.3 The June 17, 1929 Murchison (Buller) earthquake (M 7.8)

The timing of the Buller earthquake shifted much of the focus from the Arthur's Pass earthquake because of its large size and extent. It was centred on the west coast of the South Island (outside Selwyn District) approximately 15km north of Murchison (West Coast ELifelinesG 2006). It became the second largest recorded earthquake in New Zealand history and was felt over the entire Canterbury region (Yetton & McCahon, 2006). Shaking intensities at Arthur's Pass were approximately MM VI (Downes & Institute of Geological & Nuclear Sciences Limited., 1995) (Figure 3.7C), but damage was limited to items falling off shelves and minor interruptions to telephone and electricity lines (Yetton & McCahon, 2006). Geomorphic changes that occurred as a consequence of this earthquake at Arthur's Pass were minimal because much of the unstable material had been dislodged in the earthquake three months earlier (McSaveney, 1982b).

3.5.4 The June 26, 1946 Lake Coleridge earthquake (M 6.2)

The Lake Coleridge event was comprised of a number of confirmed tremors recorded over several days (Stirling et al., 2007). Numerous unconfirmed reports also surfaced that indicate there were hundreds of small earthquakes, which were not captured by recording instruments. The M 6.2 was the principal earthquake and was preceded by a M 4.3 tremor only minutes prior, and followed by numerous aftershocks that continued sporadically until the end of 1949 (Eiby, 1990). The extent of the shaking was widespread, and it was felt over most of the South Island. The epicentre was determined to be near Mt. Cheeseman in the Castle Hill Basin (Yetton & McCahon, 2006) and maximum intensities reached MM VII within a 50km radius of the epicentre (Eiby, 1990) (Figure 3.7D). At Arthur's Pass the maximum intensity was MM VI but no damage was recorded in the area.

3.5.5 The June 18, 1994 Arthur's Pass (Avoca River) earthquake (M 6.7)

The Arthur's Pass earthquake became the first well-documented seismic event in the Arthur's Pass region. The epicentre was located along a north-north-west trending fault approximately 13km south-west of the village (Berrill et al., 1995). Two M 5.8 and 5.6 aftershocks were recorded within three days of the first tremor and located approximately 15km south-east of initial epicentre (Arnadottir et al., 1995). Shaking reports extended throughout the South Island and along the southern half of the North Island, with intensities at Arthur's Pass up to MM VII (Yetton & McCahon, 2006).

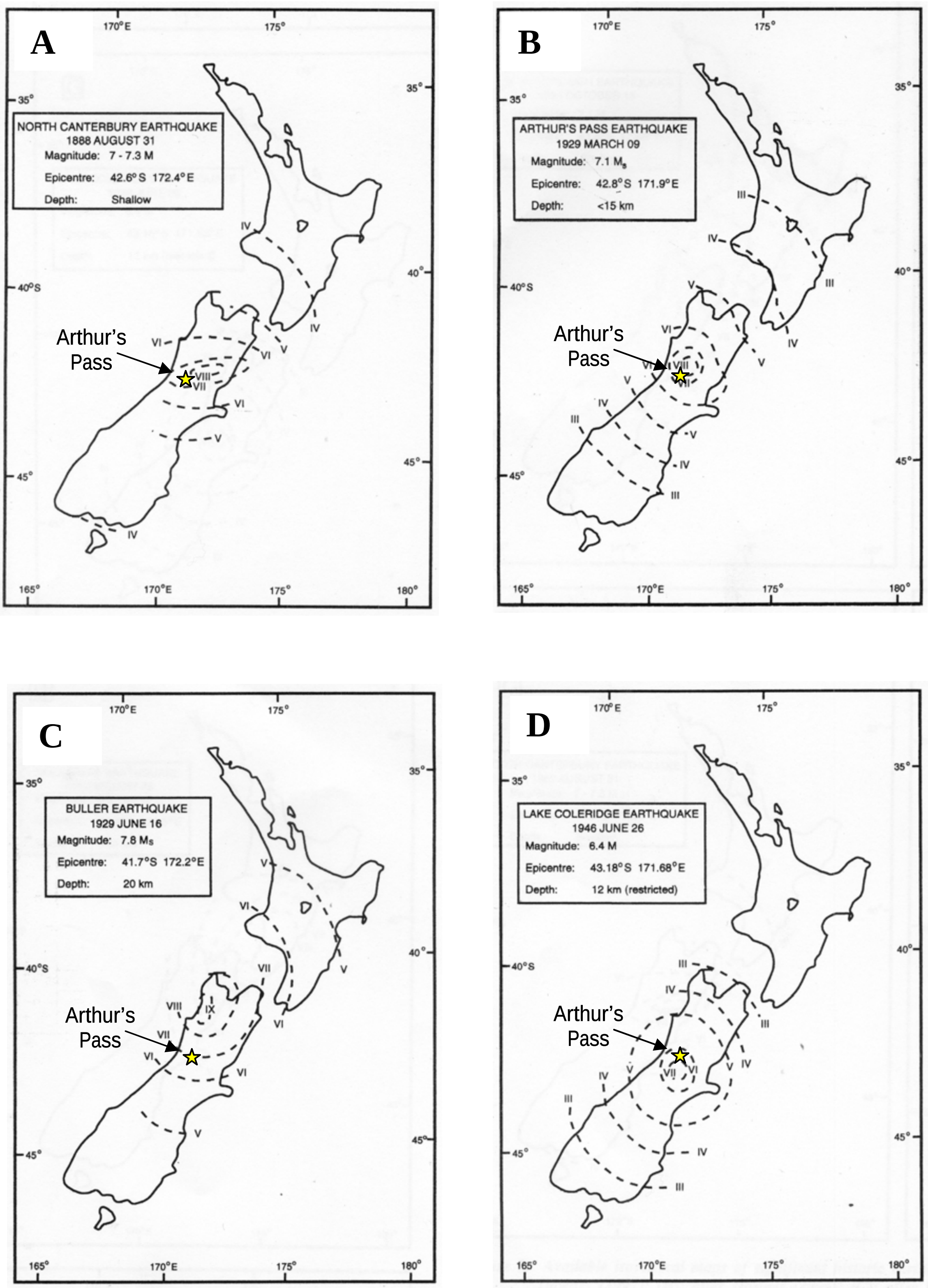

Figure 3. 7. Isoseismal maps of historical earthquakes affecting Arthur's Pass. **A.** 1888 Amuri earthquake, **B.** 1929 Arthur's Pass earthquake, **C.** 1929 Murchison (Buller) earthquake and **D.** 1946 Lake Coleridge earthquake (Pettinga et al., 2001).

Whilst structural damage to houses was limited, there was contents damage in many of the buildings (Berrill et al., 1995). In the Bealey Valley, the road was slightly affected and remained closed temporarily while minor cracks in the bitumen were filled and small rockfalls cleared away. Some embankment slumping was evident on the road in addition to rock debris from flows and dislodged boulders (Yetton & McCahon, 2006). Berrill et al (1995) also documented the high number of joint openings in highly jointed rocks near Bealey Spur and noted that many avalanches were triggered nearby. Local residents reported several fresh scars that appeared on the hill slopes surrounding the township and identified huge boulders in Rough Creek that had fallen to land in the creek bed (Vaile, 2007).

Berrill et al (1995) resolved that high rainfall was responsible for putting strain on unstable slopes and embankments prior to the earthquake, generating mass movements in the months before the earthquake. This accounted for the lack of earthquake-triggered slope failures that occurred as a result of the tremors.

3.5.6 The May 29, 1995 Arthur's Pass earthquake (M 6.0)

Although the 1995 Arthur's Pass earthquake had a lower magnitude than the earthquake a year previously, there were major differences in the severity and scope of slope failures in the Arthur's Pass National Park, with the 1995 earthquake causing the most damage (Paterson & Berrill, 1995). The earthquake had an epicentre approximately 14km west of Arthur's Pass and 17km north of the 1994 event (Yetton & McCahon, 2006). It was felt over most of the South Island.

The highway incurred the most damage but the village remained relatively intact. Two aftershocks of magnitude M 4.5 and 3.9 occurred almost immediately after the first earthquake (Pettinga et al., 2001). The epicentre had a closer proximity to Arthur's Pass than the 1994 event and as a result the steep, unstable slopes were most affected (Paterson & Berrill, 1995). Major damage was sustained along the Zig Zag section of the Otira Gorge road which was subsequently closed for several days due to debris flows and slumping. The road was closed again several weeks later when rainstorms caused additional failure of the earthquake-weakened slopes in the valley (Yetton & McCahon, 2006). South of Arthur's Pass, the shaking caused some reactivation of debris fans and slumping along the road but it was not severe enough to restrict traffic flow in the area (Paterson & Berrill, 1995).

3.5.7 The November 24, 1995 Cass earthquake (M 6.3)

The Cass earthquake is the most recent large-scale earthquake in Selwyn District, and was felt as far away as Blenheim and Timaru, with an epicentre very close to the Cass settlement. The epicentre was in fact closer to the Arthur’s Pass village than the 1929 Arthur’s Pass earthquake although it did not cause any reported structural damage at Arthur’s Pass (Gledhill et al., 2000). Some minor slope movement was triggered by the principal earthquake followed by a M 5.2 aftershock a day later (Pettinga et al., 2001).

3.6 SEISMIC HAZARD EVALUATION

The timing and location of future earthquakes affecting Arthur’s Pass cannot currently be predicted with any degree of certainty. The combination of widespread earthquake distributions and numerous source locations identify earthquakes as a dispersed hazard, which makes the prediction of future tremors difficult. There are methods of improving on “best guess” scenarios using probability models, which can assist in preparing communities for often inevitable earthquakes, but obtaining a conclusive value for the exact time and place of the next earthquake is impossible.

Historically, the most serious earthquake damage occurs in regions around the world with two features in common:

1. Environmental exposure to mountainous terrain and areas susceptible to frequent ground failure;
2. A degree of human vulnerability due to poorly constructed buildings and high population densities in dangerous areas. (K. Smith, 2004)

Arthur’s Pass is sited on an area with high physical exposure to steep, unstable slopes formed of highly-weathered greywacke, containing numerous faults. The permanent resident population ranges from 54 to 90 people throughout the year, but the large number of tourists that pass through the village expand the population significantly. Thus, the population density is comparatively high within the small section of land that bounds the village. Using this logic, Arthur's Pass village is sited in a very dangerous region in terms of earthquake hazards.

3.6.1 Classification of hazards

Earthquake hazards can be grouped into 3 categories; primary, transient and secondary (Figure 3.8). Primary effects are sustained immediately along the fault trace as a result of the fault rupture. In most cases the close proximity to the fault trace results in changes to the physical environment along the fault. Transient hazards rapidly follow initial rupture and are typically associated with ground shaking. Secondary effects occur seconds to days after the initial fault rupture, as a consequence of primary and transient processes (Kovach & McGuire, 2003). Tertiary and quaternary hazards follow some time later and are largely discussed in subsequent hazard chapters (Table 3.4).

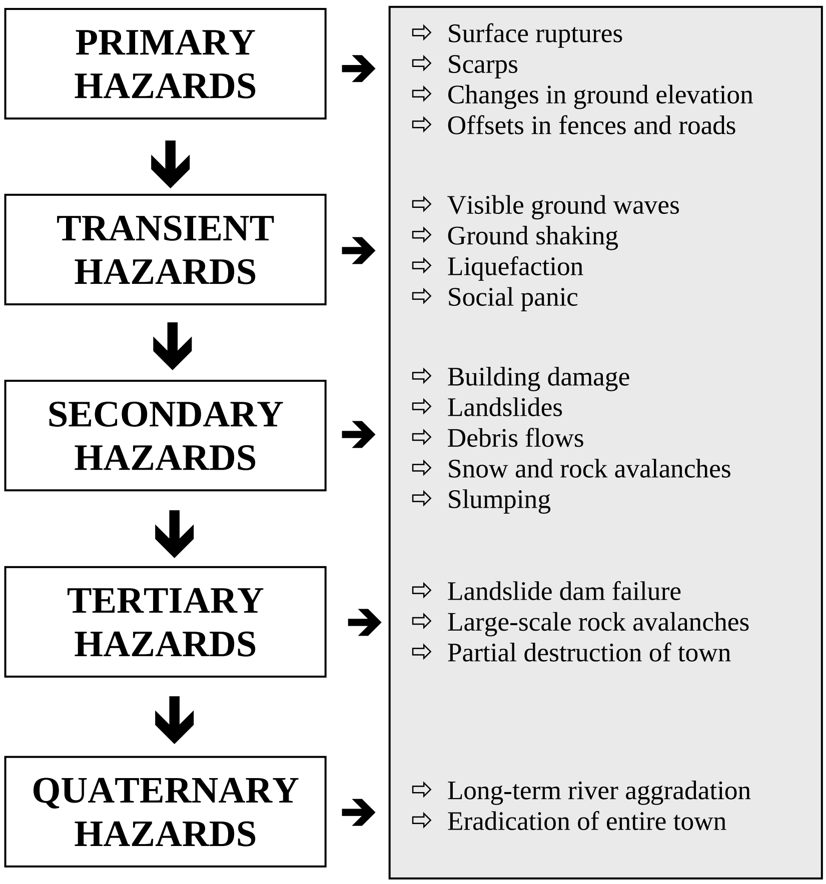

Figure 3. 8. The classification of earthquake hazards into five main categories based largely on the timing of the effects during and after the initial earthquake event. It demonstrates that the impacts from seismic events have serious ramifications to other aspects of the region, and that they are long-term and have major implications with other hazard processes (adapted from (Kovach & McGuire, 2003)).

	Consequences of subsurface fault rupture	Features resulting from consequences of fault rupture	Time frame of consequence	Time needed to restore/repair
PRIMARY EFFECTS	Surface rupture	- Scarp formation - Changes in ground elevation - Offsets in previously linear features - Ground shaking	Seconds to minutes Seconds to minutes Seconds to minutes Seconds to hours (aftershocks)	N/A N/A N/A N/A
TRANSIENT EFFECTS	Ground shaking	- Building damage - Loss of exterior lifelines (medical aid, telecommunications, food supply) - Disconnection of utilities (water supply, electricity, sewage, gas supply) - Damage to infrastructure (roads, railways, powerlines, bridges)	Seconds to hours Seconds to hours Seconds to minutes Seconds to hours	Hours to months Hours to weeks Hours to weeks Hours to months
	Social panic	- Disorder and general hysteria - Health issues pertaining to shock, post-traumatic stress and anxiety attacks	Seconds to hours Minutes to months	Minutes to days Minutes to months
SECONDARY EFFECTS	Building damage	- Houses shifting or moving off foundations - Walls, windows and doorframes becoming warped or skewed - Brick chimneys toppling - Contents damage	Seconds to hours Earthquake duration Earthquake duration Earthquake duration	Days to weeks Days to weeks Days to weeks Hours to weeks
	Slope failure	- Landslides - Debris flows - Avalanches - Slumping	Seconds to days Minutes to days Seconds to days Seconds to days	Days to weeks Days to weeks Days to weeks Days to weeks
TERTIARY EFFECTS	Landslide dam failure	- Breach of landslide dam - Flash flooding - Slow leakage of water and sediments into the village area - Partial or total destruction of village	Hours to weeks Hours to weeks Days to years Days to years	Days to months Weeks to years Days to years Weeks to years
	Large-scale rock avalanches	- Large volumes of sediment moving into the fluvial system or directly over the village area - Partial or total destruction of village	Days to months Days to years	Weeks to years Weeks to years
QUATERNARY EFFECTS	Long-term river aggradation	- Severe build-up of material near village area, blocking river channel. - Alteration of mass movement and fluvial patterns. - Eradication of entire village.	Months to years Months to years Months to years	Weeks to years Months to years Years

Table 3. 4. The hierarchy of hazards at Arthur's Pass, including their associated effects and time frames for their occurrence and repair (based on (Bell, 1999).

3.6.1.1 Primary Hazards

The lack of any active fault traces through the village area suggests that primary damage sustained directly from a fault rupture is unlikely. Scarp formation and changes in ground elevation on the slopes of surrounding mountains such as Mt. Aicken, Avalanche Peak and Mt. O'Malley may occur due to the movement of local faults, but they are not major concerns in terms of the seismic hazard in the village.

3.6.1.2 Transient Hazards

The effects of transient hazards are a very real issue to the community at Arthur's Pass. Depending on the size of the earthquake, intense ground shaking is very likely near the earthquake source, and based on the high number of earthquake sources surrounding the town, visible surface waves may be observed during an earthquake. Ground shaking is directly responsible for the majority of earthquake hazards. It can sever crucial lifelines such as roads, railways, bridges, powerlines and telecommunication links. Past experience shows that the roads, railways and bridges are particularly susceptible along State Highway 73. The road surface and bridge abutments can deteriorate from intense shaking and reinforcement of the structure is one of the only methods through which the severity of the damage can be reduced.

Because local site conditions (such as soil type, lithology, rock thickness and depth to the water table) can influence the severity of ground shaking, it is possible to deduce that the Arthur's Pass region may have the potential to reduce some of the shaking intensity of an earthquake because of its local ground conditions. The greywacke bedrock forming the Southern Alps is comparatively hard but at Arthur's Pass it is highly weathered, which makes it brittle and more prone to shearing and collapse. However, the water table is deep and there is minimal sediment material vulnerable to liquefaction processes. The soil also accommodates fertile plant habitats which produces a high degree of slope stability against minor events. In many instances, however, the ground shaking will originate from a close or large enough source that high intensity ground shaking will be unavoidable and uncontrollable.

Liquefaction processes are most pronounced on the sediment-laden Canterbury Plains, rather than in the Southern Alps. The hard rock that makes up the Arthur's Pass region makes it far less susceptible to liquefaction, and there has never been a reported incident of liquefaction in the town since first settlement. Therefore, it is it not considered a serious threat.

Social panic often accompanies a natural disaster because of the unfamiliarity and danger associated with the event. Hysteria and general disorder are typical human reactions in times of distress so it is important to have people in the area (often local residents) who have been trained to deal with the situation and can take on a leadership role. The permanent residents of Arthur's Pass have witnessed countless natural disasters on a range of different scales, and they are aware that they reside in a vulnerable position. They are often very willing to learn ways of managing the risks better and are often capable of dealing with disasters as they occur. Residents in leadership roles are able to instruct the tourist population on what to do when a major earthquake occurs and can keep them as calm as possible until outside help arrives.

3.6.1.3 Secondary hazards

The most common types of secondary hazards at Arthur's Pass are mass movements, such as landslides, debris flows and avalanches, which are triggered by intense ground shaking. Damage to man-made structures is also a major issue because earthquakes are relatively harmless on their own. When buildings are brought into the situation, a hazard is created that is very harmful to people. Most earthquake casualties are caused by building collapse and mass movements induced by ground shaking (K. Smith, 2004). Mass movement hazards are discussed as a separate component in Chapter 4 and will not be reviewed in this section. However, it is important to realise that the most hazardous mass movements are probably earthquake generated. The main building damage issues in Arthur's Pass relate to houses moving on their foundations, warped walls and doorways, smashed windows, contents damage and chimney collapse. Previous earthquake activity in the township has not been responsible for the collapse of entire houses, although the potential for it exists with a large event such as an Alpine Fault rupture.

Much of the building construction in Arthur's Pass village dates back to the early 1900's when minimal attention was paid to the structural soundness of residential dwellings. The older style houses have wooden frames, weatherboard exterior walls and tin roofs. The newer buildings are typically transportable models, made from either corrugated tin, aluminium or fibreglass with reinforced walls. The structural quality of a building plays an important role in determining whether it stands up to ground shaking or not (Burby, 1998). Experience shows that the wood-framed buildings at Arthur's Pass can cope with greater amounts of earthquake energy than the more brittle metal and stone buildings, which tend to easily buckle, crumble and disintegrate under stress.

The New Zealand Building Code was introduced in 1935 to ensure that all buildings were designed and constructed with materials that could withstand the horizontal motion caused by earthquakes. The 2004 amendment of the 1991 Building Act states that there are limits to the construction and alteration of properties that are subject to one or more natural hazards. In the case of Arthur's Pass, most of the houses were built before the Act was passed and thus did not follow any safety specifications. All buildings constructed after 1935 have some form of earthquake resistance and now many of the pre-1935 dwellings have earthquake-proof improvements. The effectiveness of the original Building Code 1935 design specifications was evident during the 1994 and 1995 Arthur's Pass earthquakes, when there was no recorded structural damage to buildings; contents damage was the only issue for residents.

3.7 REGIONAL AND LOCAL SEISMIC HAZARD IMPLICATIONS

In terms of physical and consequential attributes, there are several differences between regional and local fault sources. A fault rupture on a regional scale will typically have a higher magnitude, longer duration and more intense ground shaking over a larger area compared to a locally sourced tremor. A regional earthquake in or near Canterbury would affect a large proportion of the South Island and have substantial implications on sizeably populated centres such as Christchurch (pop. 344 000), Timaru (pop. 43 000), Greymouth (pop. 10 000) and Westport (pop. 6 000) (Statistics New Zealand, 2006).

The main concern with an earthquake of widespread consequence is that the resources available to assist small communities like Arthur's Pass would be severely restricted. Due to its isolation within the Southern Alps, and the high probability of road and rail damage during an earthquake, the only realistic method of transport to Arthur's Pass is by helicopter. If road and rail transport were possible, the help available to Arthur's Pass from outside sources would still be very limited, so the community would have to cope on its own for an indeterminate period of time.

Earthquakes at Arthur’s Pass generated from local faults may still produce large-magnitude events but the difference is that the large towns such as Christchurch and Greymouth are not as likely to be critically affected by them. Consequently, there will be more help available to the Arthur’s Pass community from nationwide resources such as search and recovery teams, medical facilities, rescue helicopters, communication centres, bulldozers and earth movers and structural engineers. This will alleviate the stress in a shorter amount of time by limiting the amount of damage caused in the village and reducing the recovery time after an earthquake.

Buildings within the village will be susceptible to shaking durations of up to a couple of minutes, with aftershocks lasting up to months after the initial shock, depending on the fault source. Heavy damage or total destruction of unreinforced masonry buildings is likely, chimneys will crumble and houses will move off their foundations (Stirling et al., 2007).

The roads along State Highway 73 and throughout the town are likely to become cracked, warped and partially removed or blocked by mass movements during a tremor of medium to large-scale. Damage to the road is a common problem in the Arthur’s Pass National Park. Temporary road closures have occurred repeatedly since the road was first established in the late nineteenth century, and are expected to continue well into the future.

The bridges along the highway and throughout the town are essential for vehicular transport but are very sensitive to ground shaking. On the eastern side of the pass near the town are the McGrath Stream bridge, Rough Creek rail and road bridges, Avalanche Creek bridge, White Bridge and the Waimakariri road and rail bridges, which are all at risk. Rough Creek and Avalanche Creek are easily crossable on foot throughout the year and McGrath Stream and the Bealey River are negotiable with the right equipment. Due to the nature of its boulder sized bedload, Rough Creek would not be passable by vehicles if the road and rail bridges were out of order.

The main powerlines roughly follow the highway. Disconnection of the power supply or uprooting of the power poles may occur as a result of ground shaking, but it is fairly simple to relocate powerlines that are in a vulnerable position. Relocation is a fairly common practice in the area and work is currently being undertaken to bury the above-ground powerlines throughout the village so that while they may still be affected by widespread earthquake activity, they are removed from other hazard processes.

Both the Vodafone and Telecom satellite towers are located in the railway yards and provide the village with full mobile phone coverage. Damage to these towers would result in the disconnection of mobile services and therefore amplify communication issues. Powerlines are currently above ground but are scheduled to be buried as part of the $2 million upgrade to the town (Department of Conservation, 2007), which will reduce the risk to power transmission in the village from earthquakes and meteorological hazards.

The drinking water is sourced locally from Avalanche Creek, and is UV-treated and filtered before reaching the buildings. Ground shaking may sever water pipes to individual houses but the lack of water is not expected to be a major issue because of the abundant and relatively clean river water from Bealey River, Rough Creek, Devils Punchbowl Creek and McGrath Stream. Contamination from sediment deposition or sewage leakage may occur in selected catchments, but the number of diverse water sources should provide at least one clean water supply for stricken residents.

3.8 EARTHQUAKE MITIGATION METHODS

The key to coping with any earthquake hazard is preparedness and preparation. Other than earthquake-proofing houses and controlling hazard zonation in the town, the only method of restricting the severity of damage after an earthquake event is to increase community resilience through hazard awareness, self-preparedness and effective response and recovery plans.

Risk reduction is carried out using earthquake protection methods, such as hazard-resistant structural designs and environmental control. Environmental control is a direct method that acts to suppress the earthquake at its source (K. Smith, 2004). Due to the complexity and abundance of faults near Arthur's Pass, this is essentially an impossible task, and more indirect methods are used. Engineering solutions such as the use of earthquake-resistant buildings have been discussed previously, and must be applied in conjunction with detailed soil and rock mechanic investigations. These investigations were not carried out during the formation of the township and as a result, the buildings are not always sited in the most ideal locations. The houses on the Rough Creek debris fan and on School Terrace have the highest risk of exposure to secondary effects, predominately from falling debris. Secondary effects will be discussed further in the mass movement hazard assessment in Chapter 4.

Avoidance solutions keep people and buildings away from potential earthquake prone areas within the town boundaries. Because of the lack of surface fault traces running through the town, surface rupture damage to buildings appears negligible and there are no specific areas that have a higher risk than others; it is assumed that the risks from primary earthquake hazards such as surface rupture and changes in ground level are low, but constant, for the entire area of the town. The main objective is to avoid zones that may be subject to falling debris or slope failure.

Creating a resilient community at Arthur’s Pass is done by educating visitors and residents of the potential risks and what steps to take in an emergency. This is discussed in detail in Chapter 8. Most residents at Arthur’s Pass have first hand experience of earthquake activity and are very aware of the everyday geological risks they are exposed to. They are very receptive of the advice given to them about ways of managing the risk and how to become more prepared for a natural disaster in the village. There is currently a small mention of earthquakes in a corner of the Department of Conservation visitor centre, but many of the tourists in the town are unaware of the seismic risks and are not equipped to deal with a major seismic event.

3.9 SUMMARY

The seismicity of the Arthur’s Pass region is higher than other areas of the South Island due to its location at the confluence of two major fault systems, and as history has shown, there is no shortage of earthquake sources or events. The principal earthquake hazard issues identified in Arthur’s Pass demonstrate that:

1. Earthquake distribution patterns show a gap in deep earthquakes along the central South Island that corresponds to the Alpine Fault location. Faults near Arthur’s Pass tend not to be represented in surface features and consequently may be overlooked by researchers, with potential for there to be large-scale tremors on previously unidentified faults.
2. The Arthur’s Pass region has been identified as the region most likely to experience the highest ground acceleration and shaking intensity in Canterbury because of its

location, with ground shaking intensities expected to reach up to MM X during a large-scale event such as an Alpine Fault rupture.

3. Both regional and local faults have been identified as potential seismic threats to Arthur's Pass village. The Alpine Fault, Marlborough Fault Zone, Harper Fault and Porters Pass-Amberley Fault Zone represent larger faults more than 15km from the village, whilst the local faults within 15km of the village are the Kelly Fault, Hura Fault, Bruce Fault, Red Rock Fault Zone, Scott Fault and Aicken-O'Malley Fault, among others. Countless unnamed and unidentified faults are dispersed throughout the region, providing a constant background risk of potentially damaging earthquakes at Arthur's Pass.
4. Historical earthquakes provide crucial information that can be used for earthquake prediction and analysis. Several significant earthquakes have affected the Arthur's Pass community in recorded history, with varied consequences. The most significant of these was the 1929 Arthur's Pass earthquake, which resulted in extensive slope failures, road closures, disruption to the railway line, property damage and social panic.
5. Arthur's Pass village is in a very vulnerable position because of its environmental exposure to earthquake hazards. Primary, transient and secondary effects associated with earthquakes such as surface rupture, ground shaking, structural damage, social panic and earthquake-triggered mass movements have the potential to heavily disrupt the Arthur's Pass community.
6. A large-scale earthquake event is likely to have serious implications at Arthur's Pass. In such an event there is likely to be loss of lifelines and services such as electricity, gas, communication lines, transport routes and sewage systems. Critically, it is possible that external resources needed for rescue and welfare will not be available to the village for a extended length of time after the event and as a result the village will have to be self-sufficient during this period.
7. As earthquakes cannot be predicted with any degree of certainty, the best earthquake mitigation methods are preparedness and preparation. Non-invasive methods such as increasing community awareness through hazard education and the implementation of effective emergency plans are the most ideal methods of earthquake management. Additionally, risk reduction can be achieved by introducing hazard-resistant structural solutions to buildings and controlling land use in hazardous areas. As a last resort, avoidance solutions may be required to remove people and buildings from potential earthquake-prone areas.

CHAPTER 4
METEOROLOGICAL HAZARDS

4.1 INTRODUCTION

This chapter is the second of four specific hazard chapters. Meteorological events contribute greatly to the natural hazard risk at Arthur's Pass and are controlled by several climatic processes operating throughout the region. Weather-related hazards can be particularly damaging because they occur frequently and repeatedly and have a concentrated intensity within a limited area. One of the prime advantages of weather-related hazards is that they can be predicted with some certainty up to several days in advance, thus allowing sufficient time for community preparedness. In most cases the threat comes not directly from meteorological processes, but from conditions that are generated by these processes, as secondary hazards. Extreme weather events are more likely to be responsible for property damage and minor injuries and less likely to be the cause of severe injury or death compared to other natural hazards.

The prime aims of this meteorological hazard assessment are:

1. To identify and define all possible hazards caused by inclement weather at Arthur's Pass village and it surrounds, including Temple Basin Ski Field.
2. To describe and analyse historical weather events that have significantly affected Arthur's Pass.
3. To determine where the hazards are most likely to generate damage and where the areas most vulnerable to specific hazards are located.
4. To analyse the projected effect of climate change and global warming on other natural hazards at Arthur's Pass.
5. To evaluate current mitigation methods at Arthur's Pass and explore possible improvements to existing mitigation methods.

4.2 ANALYTICAL TECHNIQUES

The foremost method of evaluating the meteorological hazards at Arthur's Pass is the examination and extrapolation of weather data. Because climate is so highly variable, it requires long-term observations in order to be useful. Constant monitoring of the local climate for less than several years is not sufficient to show any long-term trends, therefore, weather information obtained from several different sources has been used to conduct this analysis.

Raw climate data were supplied by the National Institute of Water and Atmospheric Research (NIWA) and extend back to 1955. Daily rainfall data and monthly temperature values for each year were available. Snow data were somewhat more limited and simply consisted of the number of days that snow fell at Bealey Spur from 1867 to 1880 and at Temple Basin from 1966 to 1982. The climate records were used to investigate trends in the daily, monthly and yearly averages at Arthur's Pass. Daily records of rainfall allowed for individual storm events to be pinpointed and examined and the monthly temperature and rainfall data were useful in obtaining averages and highlighting overall trends.

As with all hazards, past meteorological events that have caused damage or injury have been examined to determine the potential for the Arthur's Pass environment to generate future weather-related hazards. Unfortunately, they have not been recorded in as much detail as earthquakes and some mass movements, but every attempt has been made to illustrate the number of hazardous incidents that have affected the community in the past.

Determining if global climate change has an influence on weather conditions throughout the South Island of New Zealand and analysing the effects it does have is a complex task, limited in many ways by the relatively new and unexplored issues associated with global climate change. Searching for gradual changes in the weather system and finding trends that could suggest a rise in the number of harmful global events was undertaken using all available climatic data, journal articles, government reports, pamphlets and statements from local residents. Whilst climate trends were recognised in the data, it is important to note that they have been derived from only 53 years of climatic data and as such are not sufficient for long-term climate change analysis.

4.3 THE CLIMATE OF THE SOUTHERN ALPS AND CANTERBURY

The South Island of New Zealand is located within the "roaring forties"; a climatic zone predisposed to generate strong, prevailing north-westerly winds and unpredictable weather conditions. The prevailing winds deposit large volumes of rain on the west coast of the South Island before moving over the Southern Alps and travelling across the Canterbury

Plains as warm winds (Mackintosh, 2001) (Figure 4.1). The South Island landmass is positioned between a high-pressure atmospheric zone to the north and a low-pressure, windy zone to the south. This produces an alternating pattern of anticyclones (fine weather) and depressions (poor weather), delivering periods of warm north-westerly, rain-bearing winds and strong, cold southerlies.

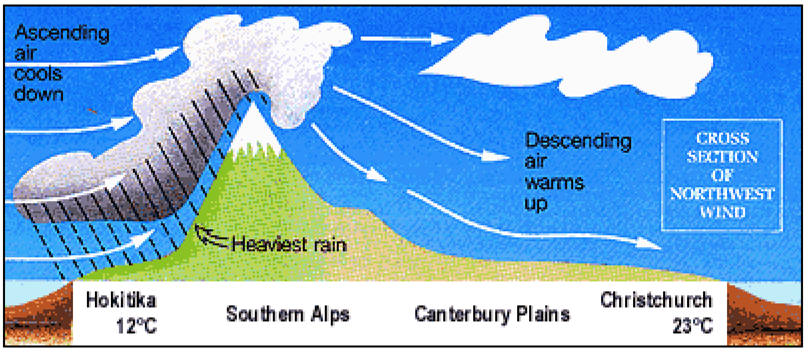

Figure 4. 1. An exaggerated account of the movement of prevailing north-westerly winds over the Southern Alps. Arthur's Pass would be located on the eastern tip of the mountain peak (Brenstrum, 1989).

It is clear that weather data fluctuate greatly between seasons and every year there are perceptible shifts in the trends of rain and temperature influenced by a series of climatic factors, including El Nino, the Interdecadal Pacific Oscillation (IPO) and global climate change.

4.4 STRONG WINDS

Strong winds are not necessarily associated with thunderstorm activity and hence are not always synonymous with rain and adverse weather. In accordance with the Beaufort Wind Scale, a strong breeze constitutes winds travelling between 40 and 50km/h. Gale force winds exceed 63-75km/h (Australian Bureau of Meteorology, 2007).

4.4.1 Wind hazards specific to Arthur's Pass

By the time north-westerly winds reach the Arthur's Pass village, a large proportion of rain has been released over the West Coast and the clouds are beginning to dissipate prior to their descent onto the Canterbury Plains. North-westerly winds bring the most severe weather conditions. They are predominantly accompanied by low intensity showers, but they can also be responsible for thunderstorms, giving rise to heavy rain, lightning and gale-force winds (Brenstrum, 1993). Southerly winds generate cold, wet conditions but are more predictable and usually short-lived.

The Southern Alps act as a barrier to the westerly winds and modify the wind patterns near Arthur's Pass. The winds are typically weaker in the winter months but gusts of over 60km/h are common through the Bealey Valley year-round (Mackintosh, 2001).

Strong winds not associated with thunderstorms are particularly apparent in the Arthur's Pass alpine area when a temperature inversion is present. A temperature inversion occurs when a thin proportion of the atmosphere (at approximately 1500m above sea level) rises in temperature abruptly as altitude increases, essentially trapping a dense, cold and humid air pocket underneath the warm inversion point and causing various weather anomalies (Australian Bureau of Meteorology, 2008). At Arthur's Pass this point usually lies just above the highest peaks, allowing for the air to be squeezed over the mountains. However, if the inversion point moves below the mountain peaks but above the alpine pass the winds become even more confined. This effectively creates a narrow, lateral belt of very strong winds that can produce gusts in excess of 100km/h (Brenstrum, 1993).

The most serious consequences of strong winds at Arthur's Pass are property damage and injury or loss of life from flying debris. Roofs and windows are very vulnerable to strong wind conditions. Sudden pressure changes within a building have the potential to dislodge unreinforced structures and create further hazards to the community (K. Smith, 2004).

Previous incidents of wind gust damage in the village have not been fully recorded, but it is suggested that the risk to the community is low, despite the persistence and high frequency of gale force winds in the Bealey Valley. The risk is rarely life-threatening if people remain indoors and stay away from vulnerable areas. There have been no reported fatalities in the Arthur's Pass village that were the direct result of strong winds. The hazard is somewhat constant throughout the whole of the township, but houses situated on the poorly sheltered land adjacent to the Bealey River are likely to be most at risk of property damage.

4.4.2 Other wind phenomena

The number of tornadoes observed in New Zealand over the last decade suggest that the number of incidents is on the rise. Most tornado activity is concentrated in the North Island in areas such as Taranaki and Auckland and along coastal South Island, in Waitame for example (Reese & Reid, 2007). There is no documented evidence for tornadoes in the

Arthur's Pass National Park. Dust storms are also unlikely because there is not enough fine particle material available for transport by wind. The conditions that induce dust storms and tornadoes rarely exist at Arthur's Pass, hence the risk is assumed to be negligible.

4.5 THUNDERSTORMS

Thunderstorms occur throughout the Arthur's Pass National Park several times a year, particularly during spring and summer when temperatures are warmer and storm cells are likely to develop (Salinger, 1998). They bring prolonged periods of intense rainfall, lightning, hail and wind gusts (Figure 4.2).

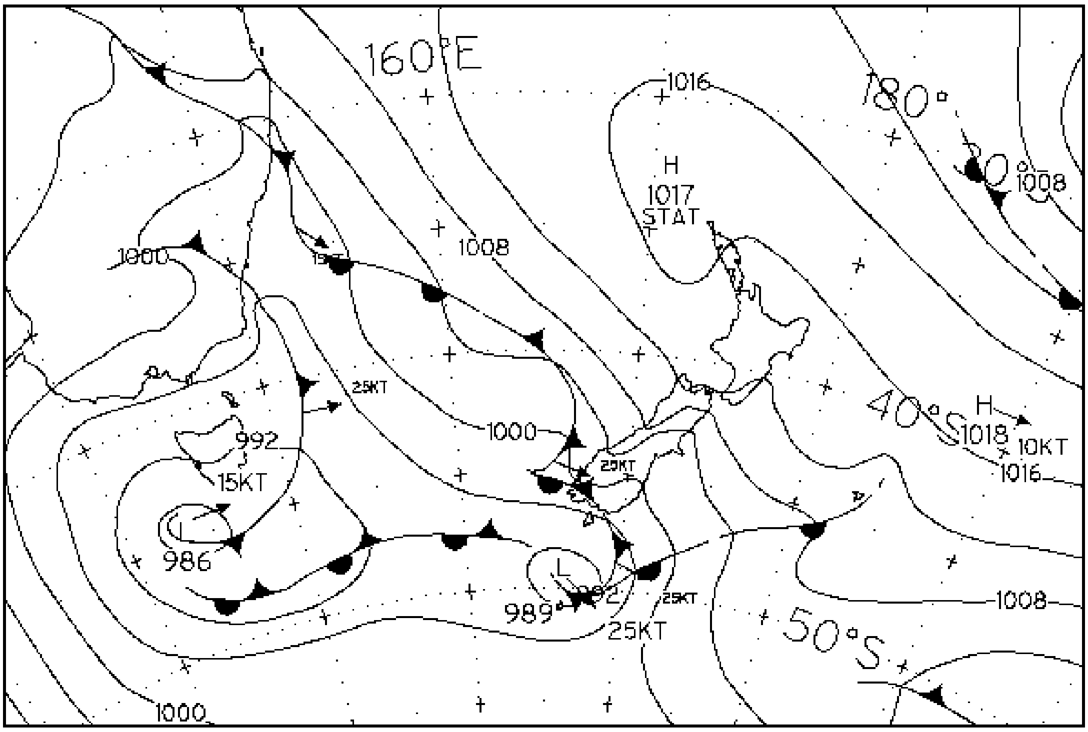

Figure 4. 2. A mean sea level atmospheric pressure analysis showing typical South Island thunderstorm conditions. This particular storm occurred on 1-5 January 2002, bringing to Arthur's Pass dense, moist north-westerly winds, heavy rain and lightning followed by cooler, unstable south-westerly winds accompanied by rain and hail. State Highway 73 was closed for a short period due to flooding and minor slips that blocked the road (Meteorology Service of New Zealand Ltd, 2002).

4.5.1 Heavy rainfall

The Meteorology Service of New Zealand (MetService) (2001) defines heavy rain as more than 100mm falling in a day, or a proportional amount falling over a shorter period of time. Heavy rains are chiefly linked to thunderstorms and often coincide with major events such as flooding and debris flows.

The most likely time of year for rain-induced hazards to occur within the Arthur's Pass National Park is early-spring through to mid-summer when rainfall is at its highest. It is not unusual to have thunderstorms and heavy rain sporadically throughout the year, but there are markedly less storms during the winter months when snow accumulation is just beginning.

Since 1955, it has rained in Arthur's Pass on average 177 days a year, approximately seven of which are days with heavy rain. The number of thunderstorms each year at Arthur's Pass averages between 5 and 9, which is loosely related to the annual number of heavy rain days because there is a clear correlation between the two events. In 1963 there were no recorded days where rain exceeded 100mm, although the record is slightly incomplete. 1958 and 1998 had the most heavy rain days at 13 each (NIWA, 2007). This demonstrates the capacity for there to be several events taking place during a short length of time, which alters the magnitude and severity of the damage sustained by the local environs.

The Arthur's Pass National Park contributes largely to the upper catchment of the Bealey confluence of the Waimakariri River. The largest catchments contributing to the Bealey River near the village include the Rough Creek (4.568km^2), Punchbowl Creek (4.251km^2), Upper Twin Creek and Twin Creek (3.750km^2), Graham Stream (2.085km^2) and McGrath Stream (3.855km^2) catchments, which all cover extensive areas and transport substantial volumes of water to the Waimakariri River confluence. Numerous other small streams extend south from the pass that supply water to the Bealey River that also contribute to the overall potential for rain-triggered hazards. The ability of local streams to carry high quantities of water is limited throughout the Bealey Valley, and therefore overloading of the fluvial channels as a result of high sediment inputs can lead to potentially destructive river flooding within the Arthur's Pass village. This is discussed further in Chapter 6.

4.5.1.1 Previous cases of rain-triggered damage in Arthur's Pass National Park.

Not all major meteorological events at Arthur's Pass have been recorded. Below are some examples of some of the most severe incidents caused by heavy rain in the village that give an indication of the risk.

The highest recorded rainfall since 1955 fell on December 2, 1979. It reached 328mm during a 24 hour period and triggered a small landslip which landed in a flooded stream channel above the camping ground at Klondyke Corner. This produced a debris flow that travelled down the stream channel and killed four campers during the night.

A series of landslips were activated during heavy rains in the months leading up to the 1994 Arthur's Pass earthquake. Most occurred in uninhabited sections of Arthur's Pass National Park but some small slips occurred along State Highway 73, causing undermining of the road foundations and forming obstructions that closed the route (Paterson, 1996). Consequently, damage sustained during the earthquake was minimised because the slopes had been denuded by the earlier rains (Berrill et al., 1995).

Most recently on November 14, 2006, 266.5mm of rain fell over a 24 hour period. It was responsible for numerous small slips that fell over the highway and closed the road. In the same instance, the Bealey River breached its first stopbank and was approximately 0.6m from breaching the second stopbank and flooding houses on the riverbank. The culvert on the western side of the road became obstructed and water was inadvertently redirected around the back of Mountain House backpacker accommodations and through to the outdoor education centre, which reported flooding of approximately 0.3m (Vaile, 2007).

4.5.1.2 Hazards associated with heavy rain at Arthur's Pass

The most prominent primary hazard presented by excessive rainfall is surface flooding (Kovach & McGuire, 2003). However, secondary hazards caused or aggravated by rain are perhaps the most serious. The extent to which high rainfall can cause slope remobilisation, river flooding, and consequential erosion of the natural environment is unconstrained. The type of mass movement and the transformation of slopes from a dormant to active stage is determined by precipitation intensity and duration (Eisbacher & Clague, 1984). Every slope surrounding the Arthur's Pass township is potentially unstable, every section of the riverbed is exposed to scour and flooding of the river is not uncommon. The village lies in the centre of this highly dynamic zone, where it is very vulnerable.

Surface flooding is a temporary hazard associated with heavy rainfall and can last from a few hours to several days at Arthur's Pass. It is a major contributing factor to fluvial flooding and flash flooding. In the mountainous areas, high slope gradients generally provide enough drainage for excess water to flow over saturated soils and accumulate in the stream channels below (Wohl, 2000). Within the village, the situation is reversed because of the low-lying nature of the ground and complications presented by the confined urban environment. Urbanisation increases surface runoff by reducing the ability of surplus water to infiltrate the ground because of the presence of impervious layers such as bitumen and concrete (K. Smith, 2004). The loss of soils into which rain can infiltrate amplifies the risk of surface flooding within the town and is mostly a threat to low-level buildings. The risk to humans from surface runoff is low, although human activities in urban areas may impact on the purity of river water by introducing contaminants such as sewage, fuel and household waste into the natural river system.

Indirect outcomes of heavy rain such as mass movements and changes to the hydrologic cycle are the most serious threats, and are discussed in detail in Chapters 5 and 6 respectively. Because the Bealey Valley is a narrow, steep passage and the village lies directly on the Bealey River floodplain, there are restrictions on either side of the current river channel due to the mountains. Consequently, there is little room available for superfluous water flow, and flooding is the only way of accommodating the extra water.

Heavy rain also diminishes visibility, produces slippery road conditions and creates dangerous circumstances for trampers in the national park. These factors may increase the likelihood of traffic and mountaineering accidents and slow down the response time of emergency services if they are required in the village, as storms lasting several days are not uncommon at Arthur’s Pass.

4.5.2 Hailstorms

Severe hailstorms are most common in the coastal regions of the southern South Island. Hail is considered to be severe if the diameter is equal to or greater than half a centimetre because at this size they are capable of causing major damage (Salinger, 1998). Inland climatic regions such as Arthur’s Pass do not generate hail-forming conditions as frequently as coastal zones and hence central areas are less susceptible to major hailstorms. Hailstorms average less than five annually in the central South Island and throughout the Southern Alps, whereas elsewhere on the eastern coast of South Island the average can be as much as 20 per year (Meteorological Service of New Zealand Ltd, 1986).

Hail typically develops over New Zealand in cold and unstable southerly or south-westerly air masses. The winter and spring months have the highest hail occurrence, but a small number of localised hailstorms occur during summer as part of convective thunderstorm activities over land (Williams, 2008). The warm, north-westerly winds that prevail throughout the summer months produce thunderstorms with distinct hail-forming conditions that give rise to significantly larger hail stones (Meteorological Service of New Zealand Ltd, 1986). The Canterbury Plains and foothills are in a prime location to receive these weather conditions and are consequently some of the most hail-prone areas in New Zealand.

4.5.2.1 Hail at Arthur's Pass

Arthur's Pass is intermittently affected by hailstorms, but most do not cause significant harm. Severe hailstorms are much more localised and are rare events at Arthur's Pass. The main issues with hailstorms, such as personal injury and property damage, become a problem when the size of the hailstones is sufficiently large to cause disruption the community and its infrastructure.

People caught outdoors in a hailstorm can usually access shelter nearby; at Arthur's Pass there is usually adequate cover in the vicinity (such as trees or buildings) to shelter under. Minor injuries may result if people are in open spaces with no available protection. The risk is rarely life threatening.

Elsewhere in New Zealand, hailstorms are often responsible for losses of crop and livestock. Arthur's Pass has a low production potential, no livestock and no established crops, which limits the impact of a severe hailstorm on the towns' economy. Tourism is unlikely to be affected by a hailstorm because even in extreme cases the impact will be moderate, have a brief duration and a short recovery time. Presently, hail is largely a nuisance to the community rather than a clear danger.

4.5.3 Lightning hazards

The peak time for lightning strikes is in the mid-late afternoon when a thunderstorm has built up to full strength (Williams, 2008). It is one of the few natural hazards for which effective protection is not readily available. Direct human contact with lightning is highly unlikely within the Bealey Valley, because of the abundance of taller, more conductive objects within the town such as power pylons, roof antennas and trees. Therefore, the direct risk to humans from lightning strikes is considered to be very low.

Even in small population centres like Arthur’s Pass, lightning can be responsible for power surges and house fires. A handful of lightning-related house fires have been documented since the formation of the township that have partially or fully destroyed permanent houses and holiday homes in the town. A “bach” on the upper northern edge of the Rough Creek fan was almost burnt down in late 2004 (Causer, 2007). The house at the time was uninhabited and the building was salvageable and later rebuilt, but this highlights the potential for small natural hazards to become serious risks in rare cases.

Due to the difficulties in mitigating lightning hazards and the low risk factor associated with them, safety measures that apply to all storm hazards should be implemented as protection against lightning strike.

4.6 FIRE

Fires have many natural sources, and are often influenced by climatic factors. Within the urban environment of the village, sources of fire ignition due to natural hazards include lightning strike and disruption to electrical lines during an earthquake. Man-made sources such as kitchen fires and those caused by candles or heating appliances are considered to be the most dangerous to humans and property. They are also expected to occur more often.

Natural scrub fires caused by lightning occur in the warmer months, although wildfires within close proximity to the town are unlikely to become life threatening because they are often noticed and dealt with whilst still in the early stages. They are fuelled by dry vegetation, especially during periods of drought, and the hot north-westerly winds driven down through the Bealey Valley.

The village has a volunteer fire brigade formed of local residents with an alarm bell and fire shed in the centre of town. This ensures immediate action is taken in the event of a fire which can potentially save many lives, because there is little time for the fire to spread and become out of control.

4.7 SNOW-RELATED HAZARDS

Arthur’s Pass is a popular winter recreational area because it receives a moderate to high amount of snow each year. The Temple Basin Ski Field is just north of the village and provides good opportunities for snow sports. Heavy snowfall is defined as more than 25cm of snow in one day, or 10cm of snow in six hours (Salinger, 1998), but in this assessment it also includes thick and sustained snow cover that disrupts normal community activities.

It is difficult to judge the true extent of snow at Arthur’s Pass because the records are very incomplete and do not hold any information on snow depth or duration, nor have they been taken directly from within the town itself. The data supplied from Temple Basin (elevation 1554m ASL) and Bealey Spur (elevation 649m ASL) are not representative of snow in the village because Temple Basin is much more elevated and therefore receives a greater amount of snow each year. Bealey Spur is likely to have conditions more similar to Arthur’s Pass, but the records document only a short interval between 1867 and 1880.

4.7.1 Heavy snowfall at Arthur’s Pass

Since the crossing of the Southern Alps through the Arthur’s Pass was accomplished in 1865, the road has been subjected to frequent closure from excessive snowfalls. In the winter of 1878, up to 4.5m of snow was recorded at Arthur’s Pass, and heavy snows stopped the Cobb & Co coach company from going through the pass for three months in 1895 (Odell et al., 1966). Throughout the 20th century, Arthur’s Pass was at the receiving end of a series of snowstorms that severely affected Canterbury and Otago, often closing the road and forcing local residents and tourists to be self sufficient for extended periods of time (Campbell, 1998).

Heavy snowfall is a primary contributor to avalanche formation, and can lead to the development of very hazardous conditions for trampers and climbers in the national park. The village now has access to snow-moving equipment, but it is common for conditions to become too dangerous for road users. In these cases, gates have been installed along State Highway 73 that close the road to traffic until the safety problems have been fixed.

Examination of the hazards resulting from snowfall were limited by the low winter snowfalls during the 2007 season. Very little snowfall persisted at the village ground level and Temple Basin Ski Field did not open as a result of the depleted snow levels (Scott, 2007) (Figure 4.3).

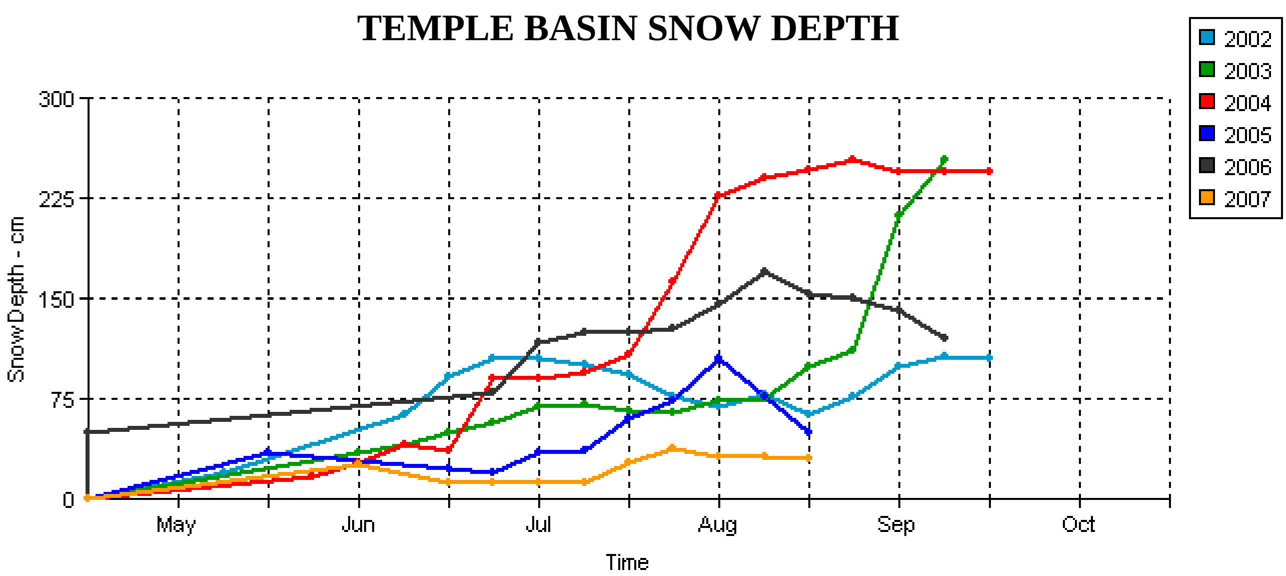

Figure 4. 3. Snow levels at Temple Basin Ski Field for the past six winters, showing great fluctuations in snow depths from year to year. The 2007 season was poor and ended early whilst the 2006 season was considered above average for snow levels (Scott, 2007).

4.7.2 Snow Avalanches

In the context of natural hazards in New Zealand, snow avalanches are regarded as relatively minor compared to more widespread threats like earthquakes and floods, and have received little attention until recently. In the past, there have been deficiencies in the level of research relating to the avalanche hazard evaluation, in terms of their causative factors, transport mechanisms and prediction. Additionally, the hazard awareness was lacking in communities with a high proportion of people undertaking recreational activities in snow conditions throughout New Zealand. Over the last 30 years, steps have been taken to rectify these inadequacies and as a consequence, a number of training courses, public information campaigns, emergency response plans and avalanche identification guides have been created to deal with these issues.

Despite the introduction of several schemes designed to reduce the incidence of avalanches and the number of fatalities caused by avalanches in New Zealand, the annual number of reported deaths is increasing exponentially over time (Irwin, MacQueen, & Owens, 2002) (Figure 4.4). This is attributed to a rise in the number of people using the alpine snow areas for recreational activities. Clearly there is a need for greater efforts in educating the alpine users and ensuring that they are taking appropriate precautions and perceiving the risk as it stands in the real environment.

Snow avalanches are most prevalent in the Arthur's Pass National Park during the peak winter months; typically between June and September. Unusually, up to 19% of avalanches occur during December and January in the upper alpine areas that contain permanent snow stores (Irwin et al., 2002). Arthur's Pass is the second most avalanche-prone area in New Zealand after Mt Cook, and the majority of avalanche activity is observed in the vicinity of Temple Basin and in the valleys surrounding Mt. Rolleston.

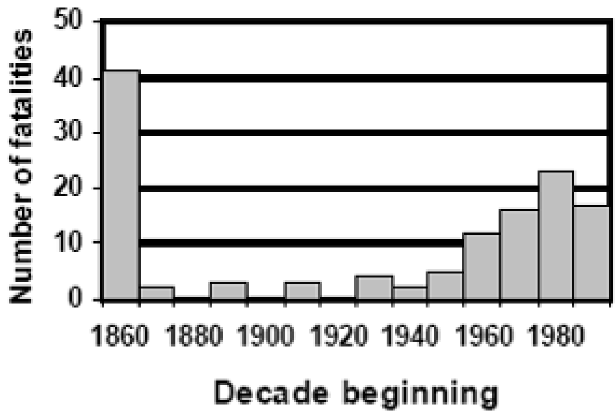

Figure 4. 4. Avalanche fatalities in New Zealand during 1860 to 1999, showing an exponential increase in the number of avalanche deaths (Irwin et al., 2002). The 41 deaths recorded in 1863 are attributed to a single event in Otago (Nelson Examiner, 1863).

4.7.2.1 Conditions for avalanche occurrence

In conducting an avalanche hazard evaluation, studying the interrelationships of four key variables is critical:

TERRAIN – The ideal slope gradient for avalanche occurrence is 25° to 40°. Slope gradients can also influence the type of avalanche, forming slab avalanches or powder avalanches. Avalanches are fundamental erosional agents and have to ability to scar the landscape quite severely.

SNOWPACK – The amount and location of precipitation and its transport by wind are primary factors in determining snowpack conditions. The snow released during a storm controls the total load on the mountain slopes and the rate of loading. Initiation of slope failure occurs when critical loading had been reached (Dingwall, 1977). The snowpack can be destabilised by secondary factors such as the local meteorological conditions. The strength of the snow and tendency to avalanche varies greatly with different crystal types.

WEATHER – 90% of avalanches occur after periods of heavy snow and during or immediately following a storm. Weather can be responsible for triggering an avalanche directly, it can increase slope stability through an increase in temperature and is able to induce fluctuations of the freezing level during storms (Dingwall, 1977).

HUMAN FACTORS – The activities of humans in avalanche-prone areas is the primary factor in the incidence of avalanches. Naturally-occurring avalanches are more predominant in Arthur’s Pass than other areas in New Zealand but most are initiated by users of the national park (Atkins, 2000).

Avalanche forecasting relies on a combination of practical skills, experience, field testing using instrumentation and semi-quantitative analytical methods (Dingwall, 1977), all of which are utilised for avalanche prevention in Arthur’s Pass. There are high variations in the average number of avalanche events per year, with large fluctuations in the number of recorded incidents throughout the national park, so it is not always possible to rely on historical data to provide an insight into future avalanches.

4.7.2.2 Avalanche zones and the risk to Arthur’s Pass village and surrounds

Extreme avalanche risk zones have been identified throughout Arthur’s Pass National Park (Table 4.1). The township at Arthur’s Pass is not considered to be at high risk of a direct avalanche flow, because the slopes forming the lower Bealey Valley are typically greater than 50° and do not often allow for excessive snow loading to occur. Avalanches are most likely to form on slopes with gradients between 25° and 40°, but it is possible for them to form in areas as flat at 15° and as steep as 60° (Schreiber, 2003). Spindrift avalanches (fine-grained snow carried by wind or falling gently) can dislodge any snow accumulations on the slopes around the village, so large slab avalanches are much less common. Spindrift deposits are rarely dangerous because they transport small amounts of snow and can be quite predictable (Kates, 2007).

Very few avalanches initiate in the forested areas – they are most often triggered in high, open areas covered by alpine scrubland and scree – but they do occur in lower elevations with seasonal snow cover. Consequently, they are not limited to the solely the upper alpine regions of the park (Fitzharris, Lawson, & Owens, 1999). Nevertheless, it is probable that the forested areas would slow down or stop an advancing avalanche before it reached the settlement.

Area	Avalanche Characteristics	Risk Factors
Bealey Valley and Rough Creek	Avalanche and avalanche-triggered rockfalls from treeline, and unstable avalanche debris throughout the valley. Powder avalanches can travel up to 700m through the base of the valley, demolishing trees through the Bealey Chasm. Trim-lines exist along the valley floor, indicating potential levels of fill from past and future flows.	MODERATE AVALANCHE BEHAVIOUR. Danger to trampers and climbers, particularly in the upper reaches of the valleys where ice and deep snow is present, and flows have the potential to fill parts of the valley.
Temple Basin	Flows occur along Twin Creek from the flanks of Mt. Cassidy and on the Downhill Basin from Mt. Temple. Phipps Peak Basin and below Temple Buttress are prone to flows from the surrounding faces. Slab avalanches occur along the Blimit ridgelines above the ski field lodges.	EXTREME AVALANCHE BEHAVIOUR. Danger to users of the ski fields, particularly in ski patrollers conducting checks in cross country areas. Destruction of ski lodge buildings is possible from flows travelling down the Blimit basin.
Crow Valley and Avalanche Peak	North of Crow Hut flows can occur through the entire valley from Mt. Rolleston, Mt. Lancelot and the ridges formed by Avalanche Peak. Flows are able to reach the head of McGrath Stream.	EXTREME AVALANCHE BEHAVIOUR. Danger to trampers and rock climbers in the valley from avalanches and rockfalls caused by avalanches, particularly when traversing Avalanche Peak.
Otira Valley	Flows from Mt. Philistine to the footbridge and along Goldney Ridge and Otira Slide from May to November. Paths are up to 1000m long and powder flows can be up to 300m vertically. Flows are capable of travelling across the valley floor and crossing the Otira River.	EXTREME AVALANCHE BEHAVIOUR. Danger to trampers on the Otira Valley walking track, and potential of damage to the footbridge cutting off access. Large flows are likely and can be initiated across most locations throughout the valley.

Table 4. 1. Significant avalanche zones in the Arthur’s Pass vicinity. Avalanches are unlikely to reach the village directly, but avalanches will have indirect implications on conditions within the village and are a major hazard to park users outside the village area (Kates, 2007).

Evidence of previous avalanches can be identified by depressions in the treeline, particularly in the upper reaches of Rough Creek and dispersed over Avalanche Peak, but in some cases it is not possible to discern previous flows if they are old because the forest has fully recovered. Since the formation of the township, there have been no confirmed avalanches within the bounds of the village, although the records are somewhat incomplete and omit any details related to injury, property damage and disruption to communication lines.

The chances of surviving an avalanche are low if the victim is buried by the flow (O'Loughlin & Owens, 1979). Despite advances in rescue techniques and response equipment, the chances of survival are more than 90% after 15 minutes, but significantly diminish to less than 30% after 45 minutes (Falk, Brugger, & Adler-Kastner, 1994).

Almost all avalanche deaths within the national park have been to recreational users of the alpine areas. Since 1926, 12 people have been killed by avalanches (Kates, 2008). By far the majority of casualties are climbers, but skiers, trampers, rescue workers and people undergoing snow-skill training have also been killed. Temple Basin Ski Field has the highest population concentration in a major avalanche-prone area and regular avalanches occur there. Avalanche control work is currently undertaken at Temple Basin.

There may be potential for isolated avalanche events within the township in the future as average temperatures increase and the snow becomes more unstable, but presently the risk is low. Away from the village, however, the risk to trampers, climbers and skiers is very high as they traverse across much more avalanche-prone zones.

4.7.3 Black ice and frost

Black ice is a concern both on the roads and on village footpaths, although it is more of an individual risk and is unlikely to cause injury the town on a large-scale. It is also a very temporary hazard and is typically only evident during the winter and early spring months when temperatures drop quickly enough at night for the ice to form. In the past people have been treated for back injuries, bruising and lacerations as a result of falling on black ice, and car accidents associated with black ice on the roads are a recurring hazard each year (SoftRock NZ, 2008a).

4.8 CLIMATE CHANGE AND GLOBAL WARMING

Climate change and global warming have become major environmental and political issues throughout the world in the 21st century. Both are showing signs of having a profound effect on the incidence and severity of natural hazards and on their impact on physical resources, societal effects and the economic costs associated with more disasters.

There is conclusive evidence that human activities have interfered with the Earth's natural climatic patterns in the last 10 000 years (Kovach & McGuire, 2003). The effects of climate change manifest as direct changes to global, regional and local climate such as changes in temperature and rainfall averages, and as secondary effects such as damage to essential infrastructure and economic losses (O'Donnell, 2007).

Climate change is regarded as any prolonged change or shift in climatic trends, over highly variable spatial and temporal scales (K. Smith, 2004). A sustained shift of more than 10 years is widely accepted as constituting climate change. It can be caused both by natural processes and human activities and is fundamentally an alteration of the chemical composition of Earth's atmosphere (O'Donnell, 2007).

Global warming refers specifically to a consistent measured increase in the annual surface temperature of the Earth, which is likely to trigger changes in other climatic phases (K. Smith, 2004). It has far-reaching consequences for environmental hazards. Global warming can easily be considered as a natural hazard because it is dealt with in much the same way as other natural hazards. A government's adaptation to global warming includes the improvement of strategic infrastructure to cope with natural hazard situations brought about by the effects of climate change so it is dealt with in much the same way as other natural hazards.

4.8.1 Global climate change

The general consensus among scientific experts is that human activities have been largely responsible for the increase in global surface temperatures in the last 50 years. There is overwhelming scientific data on past trends to support this statement (Figure 4.5). However, it is considerably more difficult to calculate the projected reaction of Earth systems to such climatic modifications (New Zealand Climate Change Office, 2004).

Several global climate changes have already been observed:

- The 1990’s have been identified as the hottest decade since records began in 1850.
- Average global surface temperatures have increased by approximately 0.74°C since 1900.
- Irreversible accumulation of greenhouse gases has taken place over the last century.
- There has been a rise in the average global sea level of 0.17m since 1900.
- The warming trend in the last 50 years compared to the last 100 years has almost doubled to an average warming rate of 0.13°C per decade.
- There has been a marked increase in the incidence and economic, social and environmental consequences of natural disasters over the last few decades.

(O'Donnell, 2007)

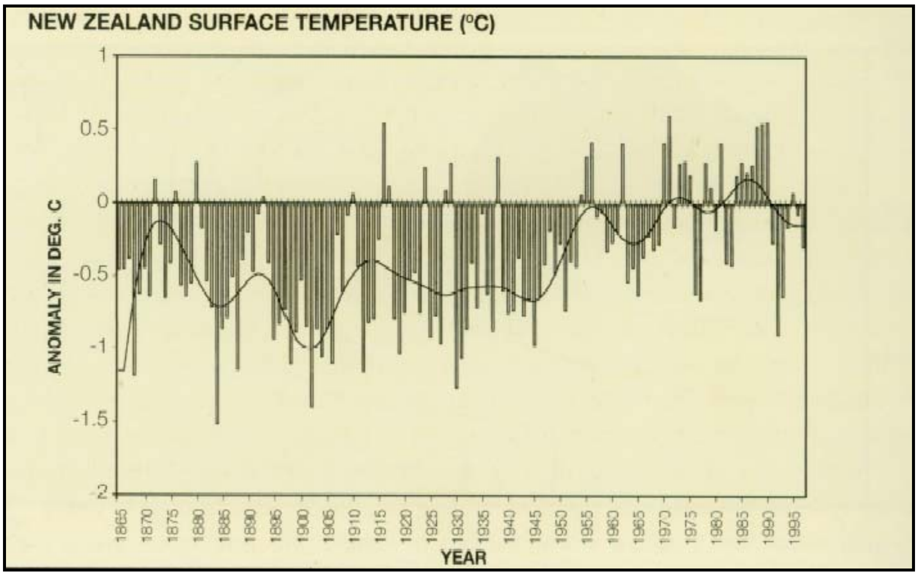

Figure 4. 5. New Zealand average annual surface temperature trends for the period 1865 to 1997 show an increase in average surface temperatures which may be attributed to climate change and global warming ((NIWA, 2007) in (Salinger, 1998)).

Smith (2004) argues that the statistical probability of most extreme natural events is not well understood and that natural disasters occur infrequently enough that any perceived increase in weather stress could be attributed to atmospheric variation rather than global warming. Similarly, it is possible to reason that a percentage of natural disasters supposedly caused by the effects of global warming could be attributed to increases in the exposure and vulnerability of humans to such disasters. Also, it is impossible to precisely determine how much of the recorded climate change is anthropogenic and therefore how greatly human activities are contributing to the overall condition of the atmosphere (K. Smith, 2004). However, much of the most recent research shows that there has been an observed increase in extreme meteorological trends, which is consistent with global warming (Australian Bureau of Meteorology, 2002).

The effects of global warming may not be immediately apparent, and it is expected to take several centuries before the full effects are experienced (Australian Bureau of Meteorology, 2002). Similarly, once the issue of global warming has been addressed and action taken to reverse the effects humans have had on the environment, the trends will continue to increase because the environment has a lagged response to these processes.

4.8.2 New Zealand climate change projections

Each region in New Zealand has its own climate-related vulnerabilities and priorities due to variations in the local climate and environmental conditions (Wratt et al., 2004). A New Zealand climate change scenario has been devised by NIWA that suggests we can expect to experience:

- A rise in the annual average surface temperature of +0.5-0.7°C by 2030 and +1.5-2.0°C by 2080 (if steps are taken now to reduce greenhouse gas emissions).
- Fewer frosts and more hot days.
- More moisture in the air and greater evaporation of moisture in the atmosphere.
- Windier conditions, particularly with prevailing westerly winds.
- Changes in current rainfall patterns (more rain in the west, less rain in the east).
- More frequent incidents of heavy rain.
- Reduced snow cover, shorter seasonal snow episodes, glacial retreat and changes to snowline locations.
- Sea level rise of 0.3-0.5m by 2100. (O'Donnell, 2007; Wratt & Mullan, 2006)

Because the significant impacts of global warming may not be experienced for some time, it is necessary to plan for such events in order to minimise negative impacts and take full advantage of any opportunities that may arise in the future (New Zealand Climate Change Office, 2004). The principal message for emergency planners is that the outcomes of climate change and global warming can be deconstructed into manageable parts and dealt with as part of existing council planning and operational processes (Wratt et al., 2004).

4.8.3 Canterbury and Arthur's Pass projections

Complex interactions exist between climate change, global warming and the Canterbury environment. Climate change is expected to increase the unpredictability of other natural hazards (Tompkins & Hurlston, 2005). The changes monitored at Arthur's Pass as a result of global warming are predicted to have very different characteristics to other regions of Canterbury, New Zealand or the world (Table 4.2). Often these changes are acutely interrelated with other processes leading to the creation of feedback loops and dependencies.

4.9 TREATMENT AND PREVENTION OF METEOROLOGICAL HAZARDS

Meteorological events are some of the most common hazard occurrences in Arthur's Pass although they can be difficult to mitigate because they are so widespread. One advantage they have over other hazards is that they can be predicted, which allows time for people to be prepared for their arrival. Like earthquakes, they are a "driving" force and consequently cannot be controlled or prevented.

Experience shows that the best form of physical preventative treatment for meteorological hazards is through the reinforcement of buildings and adequate securing of roofs and other vulnerable structures in high risk areas. During excessively windy periods, Civil Defence and Emergency Management maintains that certain steps should be taken to avoid injury and reduce damage to property. These include opening a window to equalise atmospheric pressure within the building, staying indoors away from the windows and securing outdoor items that may create a hazard to others if picked up by gusts of wind.

Treatment of surface runoff problems requires the use and maintenance of a functional drainage system, free of blockages and able to cope with large volumes of water. Previous surface flooding within the town has been made worse by the failure of drainage culverts to provide an outlet for water into the Bealey River (Vaile, 2007). Additionally, the use of more permeable materials in town construction may limit surface floods and allow for better infiltration of runoff into the ground (K. Smith, 2004).

CLIMATE CHANGE TREND	STATISTICS	EFFECTS
Rise in average surface temperature	- Average surface temperatures in Canterbury are expected to rise +0.0-1.4°C by 2030 and +0.0-3.9°C by 2080. - Greatest warming is projected to be during the winter months.	- More potential for drought. - Increased lightning and/or wildfire risk. - Melting of permafrost and glacial retreat, affecting soil and slope stability. - Increased atmospheric moisture content.
More extreme hot days	- Significant increases are predicted in the number of days per year exceeding 25°C.	- Hotter average temperatures. - Increased lightning and/or wildfire risk. - Increased melting of snow, leading to greater water flow through alpine rivers.
Fewer frosts	- Significant decreases are predicted in the number of frost days per year.	- Less permanent snow at higher elevations. - Shorter snow season. - Increased average temperatures.
Greater evaporation	- Excess evaporation removes heat from the atmosphere, stirs cooling winds and leads to increased cloud cover and storm conditions.	- More potential for drought. - Increased snow melting, glacial retreat and relocation of snowlines. - Loss of vegetation due to drier conditions, leading to slope instabilities. - Mixing of cooler winds leading to more severe and frequent severe wind and storm events.
Increase in air moisture	- For every 1°C increase in temperature, the atmosphere can hold approximately 8% more moisture.	- More intense precipitation and more severe storms. - Increase in snowfall at higher elevations due to warmer air holding more moisture.
Windier conditions	- Increase in severe wind events with up to double the frequency of winds greater than 30m/s by 2080. - Increase in the average westerly wind strength and frequency across New Zealand are predicted.	- Damage to lifelines, services and buildings. - More extreme wind events and severe storms.
Increased rainfall	- Significant increases in precipitation are expected in the Southern Alps, particularly during the winter months. - Extreme variations will be observed throughout the country.	- The Bealey River and Waimakariri River could maintain or possibly increase flows to accommodate excess water inputs. - Greater incidence of extreme natural events, such as flooding, landslides and debris flows. - Threats to essential lifelines and services.
More heavy rain events	- Increased rainfall depth as temperature rises due to 8% more moisture with every 1°C of temperature rise. - Heat that comes from the condensation of increased moisture is expected to make storms more intense. - Increases in temperature and westerly wind will lead to increases in both maximum and average catchment rainfall depending on rainfall duration.	- Increased erosion and sedimentation to some riverbed areas. - Greater frequency and distribution of debris flows, landslides and floods. - Damage to man-made drainage networks and sewage systems in the village area and destruction of property due to natural hazard events. - Threats to low-lying infrastructure and property.
Changes in snow patterns	- The elevation of the snow line is expected to increase as average temperatures increase, leading to more extreme snow events.	- Reduced snow cover, shorter seasonal snowfall, glacial retreat and snowline relocation. - Changes in the frequency and distribution of avalanches.

Table 4. 2. Projected climate change trends and their effect on atmospheric, environmental, infrastructural and social conditions at Arthur's Pass (Revkin, 2008; Wratt & Mullan, 2006; Wratt et al., 2004).

Storm activity is a frequently recurring hazard at Arthur's Pass and there is no way of removing the risk altogether. The processes of heavy rain, hail, strong winds and lightning pose a moderate to high risk to both individuals and the community within the village because the major issues they present may easily cause injury and property damage, but are unlikely to cause death.

However, the circumstances of storm damage are different for trampers and people not in the urban centre of Arthur's Pass because they are more vulnerable to the changing weather conditions. One of the major warnings given to park users refers to the unpredictability of the weather within the Arthur's Pass National Park. On numerous occasions trampers and climbers have had to be rescued because of errors in judgment and underestimation of alpine weather conditions. Since 1926, 3 people have died from complications arising from bad weather conditions (Kates, 2008) and many more have required medical treatment.

Currently, several hazard mitigation measures are in place in the Arthur's Pass National Park to minimise the risk posed by meteorological hazards.

- Daily weather information and reports on expected rainfall, wind speeds, snowpack conditions, and avalanche risk and avoidance zones are supplied by the Department of Conservation at the visitor centre in the village.
- Regular courses aimed at identifying potential avalanche zones and training for avalanche rescue are conducted at Temple Basin Ski Field.
- Emergency and evacuation plans in place within the village, although there is potential for them to be improved in the future. Temple Basin Ski Field has a very detailed emergency plan in place and regular avalanche awareness and human safety briefings are given to ski patrollers, mountaineering clubs and groups visiting the region.
- The reinforcement of structures to comply with site-specific regulations set out in the Building Act 2004. Examples of these regulations include appropriate roof pitches to avoid snow loading and flood-proofing buildings, especially those close to the Bealey River bank (Costello, 2008).
- Several publications on field safety, rescue techniques and guides to the identification and evaluation of natural hazard sites have been produced and are being distributed to park users.

Hazard mitigation measures are consistently being assessed and improved and show an advance in avalanche hazard management compared to 50 years ago, when the risks were deemed less significant. Ideally, elimination of the risks is the best method of treatment, but not always possible in public lands such as the national park. Minimising and isolating the hazards by informing people of the danger zones, monitoring prone areas and providing opportunities for advanced training are the best methods of controlling the natural hazards in Arthur’s Pass National Park.

4.10 SUMMARY

Meteorological hazards are possibly the best understood hazards in New Zealand, because they occur so frequently and can be predicted with a reasonable degree of certainty, up to days in advance. This allows for a greater level of preparedness at community level so the impact from these hazards can be minimised.

Through this meteorological hazard assessment it is possible to surmise that:

1. The New Zealand climate shows unique characteristics that are conducive to the formation of extreme weather events. Meteorological hazards identified at Arthur’s Pass include strong winds, thunderstorms, heavy rainfall, hailstorms, lightning, fire, and snow hazards such as heavy snowfall, avalanches and black ice. Climate change and global warming have also been recognised as significant natural hazards, because they have major consequences on the frequency and severity of other natural hazard events.
2. Weather-related hazards are widespread and their behaviour varies greatly. They form both direct and indirect hazards, although secondary effects are potentially the most common and harmful. Indirect effects of weather-related hazards include surface flooding through excessive rainfall and snowmelt, slope instabilities from erosion and soil saturation, fire caused by lightning strikes, the initiation of snow avalanches due to human activities and road closures due to heavy snowfalls.
3. There have been many cases of extreme meteorological events at Arthur’s Pass, of sufficient magnitude to cause injury, property damage and even death in some cases. The largest threat is to users of the national park, outside the village boundaries, who are more vulnerable because of their greater exposure to weather events.

4. In many cases specific meteorological hazards have interactions with other weather related processes and form complex relationships with other natural hazards. Meteorological events are a primary trigger of other natural hazards such as mass movements and fluvial processes such as erosion, sedimentation and flooding. This makes it all the more important for climatic behaviour to be understood for hazard mitigation and prevention to be achieved at Arthur’s Pass.
5. Climate change and global warming have become primary global issues and their impacts cannot be ignored. It is projected that global warming exacerbated by human actions will be responsible for profound climatic changes at Arthur’s Pass in the future, including an increase in average surface temperatures, decrease in frost days, windier conditions, increased rainfall and a change in snow patterns. The relationships between climatic conditions, global warming and natural hazards are complex but it is certain that climate change will increase the number of extreme natural events and amplify the unpredictability of such incidents.
6. Current major treatment methods for meteorological hazards at Arthur’s Pass take the form of physical mitigation such as structural reinforcement, building adaptations and the use of capable drainage networks. Educating the public is the most effective way of conveying the risk to the public and preventing the exposure of the community to unnecessary risks. Information is given to the public at Arthur’s Pass via weather reports from the visitor centre every day, in regular training courses, through publications outlining the hazards and within the emergency plan distributed to resident and businesses in the community.

CHAPTER 5
MASS MOVEMENT HAZARDS

5.1 INTRODUCTION

This chapter is the third of four specific hazard chapters. Landslides and associated slope processes are some of the most prominent natural hazards in the Southern Alps. Mass movements, particularly landslides, are discrete events that are responsible for less costly but more widespread disaster events than earthquakes or floods (Bell, 1999). Not only are landslides a major threat to communities, but small slips affecting major infrastructure, debris flows threatening lives and property and soil creep altering usable land all negatively affect the Arthur's Pass community in some way. Sometimes these processes can be catastrophic, other times they may just be an inconvenience. The mountain environment at Arthur's Pass leaves the township vulnerable to both large and small-scale slope processes.

The objectives of this mass movement assessment are:

1. To describe various mass movements types present at Arthur's Pass, such as slides, rockfalls, debris flows and soil creep.
2. To examine mass movement controls, especially with respect to their trigger mechanisms, mode of transport, environmental setting and preconditions for their occurrence.
3. To identify the areas at Arthur's Pass that have a history of previous slope weakness and interpret which zones may be prone to slope failure in the future.
4. To estimate the probability of occurrence for all mass movement events at Arthur's Pass.
5. To examine current mitigation methods for slope stabilisation at Arthur's Pass and investigate treatment methods that may be suitable in reducing the mass movement risk to the village and road and park users.

5.2 ANALYTICAL TECHNIQUES

A combination of in-field investigations and remote analysis was used to recognise potential mass movement sites in the Arthur's Pass area. Field reconnaissance helped to identify landslide-prone areas and find tributaries exposed to recurrent debris flow activity. Records of minor rockfalls, soil creep and slumping were taken from field observations to assist in identifying as many hazardous areas as possible.

In regions where field observations are not feasible, aerial photographs from 1938, 1943, 1960, 1977 and 1998, and Google Earth satellite images from 2007, have been used to identify fresh failure scars on neighbouring mountain slopes and to search for signs of possible weakness that may indicate areas of failure in the future. The nature of vegetation on slope surfaces is used as an aid in identifying zones of past weakness. Patches of regenerated tree and plant cover indicate that the slope has restabilised. Conversely, fresh scars indicate reactivation of the mountain deposits and highlights points of interest in this hazard assessment.

Research into mass movement hazards in the national park tends to target the Otira rock avalanche area (on the western side of the Main Divide) and the innumerable small-scale slope failures that frequently affect State Highway 73. Very little literature exists on specific failures in the township vicinity, so assumptions on the relative frequency and distribution of mass movement events have been constructed using examples from elsewhere in the Arthur's Pass National Park.

5.3 CONTROLS ON SLOPE MORPHOLOGY

The downslope migration of slope materials can be through flowing, sliding, lateral spreading, falling or toppling (Duff & Holmes, 1993). International terminology used to define various mass movements is often ambiguous and highly variable. Varnes' (1978) landslide classification scheme is one of the most widely applied schemes for New Zealand environments and forms the base for this hazard assessment (Figure 5.1). A comprehensive list of the mass movement hazards and their specific attributes at Arthur's Pass shows that several different types of hazards are recognised in the region (Table 5.1).

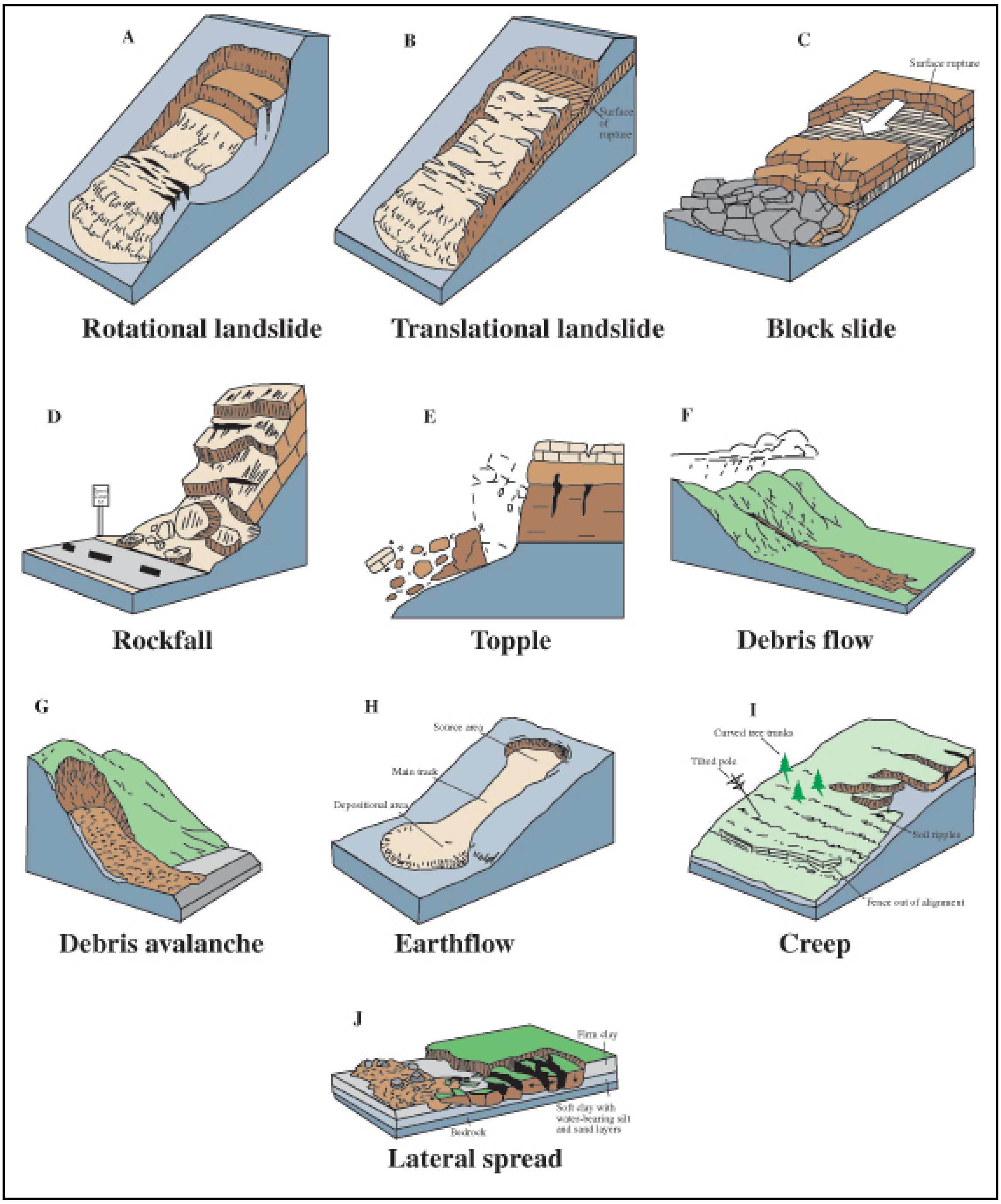

Figure 5. 1. Varnes' (1978) classification system, dividing mass movements into slides (A, B and C), falls and topples (D and E) and flows (F, G, H, I and J).

Mass movement	*Examples*	*Type of material*	*Transport velocities*	*Relative frequency in Arthur's Pass region.*	*Expected size and extent*
SLIDES	Landslide A, B, C	Predominantly bedrock with some debris and/or soils, and moderate water saturation.	Slow to extremely rapid (1.5m/month-100m/sec)	Small-scale landslides are very common, possibly even a daily occurrence. Large-scale landslides occur less frequently (approximately every few years) depending on seismicity and storm activity.	Minor to large (several m^3 to thousands of m^3). Can potentially occur on all slopes at Arthur's Pass.
	Rock avalanche A, B	May contain disaggregated rock fragments, snow, ice and soil debris.	Moderate to extremely rapid (1.5m/day-100m/sec)	Infrequent/rare, occurring every few thousand years. Several have been identified in APNP ranging from Crow Stream (6100yrs BP), Falling Mountain (1929), Otira (2000yrs BP) and Twin Fall Stream (1929).	Moderate to very large (hundreds to millions of m^3). Occur on large, very steep slopes, often above the treeline.
	Rock slump A, B, C	Weathered bedrock, soil debris, alluvium and colluvium material and/or ice and snow.	Extremely slow to moderate (0.06m/yr-1.5m/day)	Small-scale slumping is evident up to several times a year, coinciding with earthquakes and storm events. Large-scale, catastrophic slumping is likely to have a recurrence interval of thousands of years.	Minor to very large (several m^3 to millions of m^3). Occur on weathered and sheared slopes that can accommodate rotational slumping of the material.
FALLS AND TOPPLES	Rockfall A, B	Unconsolidated bedrock fragments, typically dry.	Rapid to extremely rapid (2-100m/sec)	Minor rockfalls are very common, occurring almost daily. Larger rockfalls typically coincide with major earthquakes, which may occur several times in 100 years.	Minor to moderate (several m^3 to thousands of m^3). Common on bare scree slopes, near waterfalls and cliffs.
	Topple A, B	Bedrock blocks and minor amounts of debris. Fluids in cracks may initiate failure.	Rapid to extremely rapid (2-100m/sec)	Similar to rockfalls.	Minor to moderate (several m^3 to thousands of m^3). Common on bare scree slopes, cliffs and undermined rockfaces.
FLOWS	Debris flow A + B	Loose soil, rock fragments, boulders, organic matter air and water, forming a very dense slurry with up to 50% fine material.	Rapid to very rapid (0.3-3m/sec)	Uncommon, requires specific slope and precipitation conditions to occur. Restricted to a couple of events over 100 years.	Moderate (hundreds to thousands of m^3). Fairly localised, restricted to gullies and fan heads.
	Soil creep C	Typically thick loess deposits, including soil, organic debris and alluvium and colluvium particles.	Imperceptible to slow (0.06m/yr-1.5m/month)	Continuous and repetitive, taking place on a daily basis, although not to an extreme degree at Arthur's Pass.	Minor to moderate (several m^3 to hundreds of m^3). Typically on soil covered slopes without sufficient vegetation for support.

Table 5. 1. The mass movement classification scheme with expected magnitude and frequency in the Arthur's Pass area. A = Seismic-triggered, B = Precipitation-triggered, C = Other, slow-moving types (Cave, 1987; Highland, 2004; Kovach & McGuire, 2003; Sharpe, 1968; Varnes, 1978).

5.3.1 Mass movement terrains and triggers

Alpine slope processes are very active in the Arthur's Pass region and hazards from mass movement disasters have steadily grown as the use of mountainous land increases (Whitehouse & Griffiths, 1983). It has been determined by Jones (1995) that landslides and mass movements are more likely to take place within specific terrains, all of which translate to the Arthur's Pass region and are recognised as unalterable features of the local setting:

a) Areas subject to seismic shaking
b) Mountainous environments with high relative relief
d) Areas with high rainfall

In order to accurately assess the mass movement hazards at Arthur's Pass it is necessary to understand the methods through which they occur and the processes taking place in the local environment that contribute to the apparent risk. Owens et al (1994) group landslide hazards as:

a) Those triggered by seismic events
b) Those triggered by atmospheric events
c) Other, slow-moving types

5.3.1.1 Atmospherically-driven mass movements

In the short-term, precipitation is the most common driving force behind mass movement activity, and is responsible for initiating many small-scale mass movements and a number of large-scale slope failures. However, Whitehouse and Griffiths (1983) surmise that large rock avalanches in the Southern Alps have a return period of approximately 100 years and that very few of these are storm-related. Slope movements resulting from storm conditions include regolith failure, weathered bedrock failures, erosion, slides and debris flows (Owens et al., 1994). Flood damage is known to increase the mass movement risk by exacerbating slope weaknesses through undermining, erosion and water infiltration of rocks.

Whitehouse and McSaveney (1992) hypothesise that the most critical factor in precipitation-triggered slope failures is the rainfall intensity and duration. Rainfall with a high, short-term intensity has been found to mobilise landslides and debris flows much more efficiently than long duration storms with lower rainfall intensities. This theory is used to explain the widespread damage sustained during the 1957 and 1979 storms and the lack of similar damage on a more regular basis. Caine (1980) determined that a threshold exists between rainfall duration and shallow mass movement incidence, which Dingwall et al (1989) applied to New Zealand national parks. The outcome suggested that up to 85% of the area within a designated national park area is susceptible to failure every five years, dependent on suitable slope and regolith conditions.

5.3.1.2 Seismogenic mass movements

Earthquakes have a greater recurrence interval than storms and heavy rainfall and as a result they are liable to generate large-scale, localised mass movements that are not as easily treated as storm-driven events. Keefer (1984) studied a series of earthquake-generated mass movements with the aim of classifying various types of landslides. The results suggested that there are four types of mass movements initiated by weak shaking. These included rockfalls, rock slides, soil falls and soil slides. Deep-seated, lateral spreads require strong seismic shaking, and some large-scale rock avalanches require very disruptive seismic shaking to initiate.

Earthquakes can act directly on a slope by causing enough ground shaking to dislodge slope material, or they can activate secondary processes and be a catalyst in some areas where ground shaking dilates soil on sloped surfaces and allows for infiltration of rainfall more rapidly. This leads to a reduction in the shear stress of the slope materials and results in slope failure (Highland, 2004). Additionally, widespread rockfalls are commonly triggered by earthquakes that loosen the rocks and make them available for transfer. Earthquakes also indirectly trigger mass movements through fault activity, which can potentially create steep and unstable slopes along weak fracture points (Jochim & Colorado Geological Survey, 1988).

Secondary and tertiary seismic hazards often manifest as mass movements (Figure 3.10). Secondary hazards initiated by earthquakes include debris flows, landslides, rock avalanches and slumping, whilst tertiary hazards are associated with landslide dam failures and large-scale rock avalanche events, illustrating that mass movement occurrences often rely on earthquake events.

5.3.1.3 Other mass movement triggers

Slow-moving mass movements, such as soil creeps and slumping are also long-term hazards and often go unnoticed, not allowing for remedial treatment in the early stages of creep development. Other than minor examples of soil creep, few slow-moving types of mass movement have been identified in the Arthur's Pass vicinity.

5.3.2 Preconditions and causative factors of mass movement hazards

Several causative elements simultaneously work together to generate mass movement events. These elements are frequently interrelated and are capable of generating highly complex slope conditions (Owens et al., 1994). They can be categorised into two groups; internal and external mechanisms. External driving forces place stress on the slope from the local environment, which acts to reduce the internal shear stress of a slope and increase the chance of failure (Bell, 1999). Internal mechanisms operate to reduce the shear strength of a slope to a point below the external forces applied to it by its environment, causing the slope to fail (Bell, 1999). These forces are either triggering mechanisms or pre-existing conditions of slope morphology (Table 5.2 and 5.3).

EXTERNAL FORCES	
Climatic conditions	The incidence of mass movements in the national park is heavily reliant on local hydrological conditions, including antecedent and persistent rainfall and snowmelt, which all supply high volumes of water to the river system (E. Smith, 2004). The frequency and magnitude of storms is a critical factor to the frequency and magnitude of mass movements.
Transporting agents	The presence of air, water and ice strongly correlates with the rate of sediment transport within the geomorphic environment. High quantities of transporting fluids have to ability to move great volumes of slope materials. This is illustrated by the high erosion and aggradation rates along tributaries in the Bealey River catchment.
Vegetation characteristics	It is difficult to assess the role of vegetation on slope stability, but plants and trees may help to bind slope materials and reduce the capacity for slope failure (Cave, 1987). However, in poorly consolidated areas, vegetation may negatively impact slope stability by placing extra weight on the slope that cannot be supported, leading to slope failure.
Weight of slope material	Slope materials are made heavier by the presence of vegetation and snow accumulations. The lithology of the slope also affects the weight of slope materials, as does the degree of water saturation (K. Smith, 2004).
Soil characteristics	The thickness, type, porosity and saturation of soil affects surface runoff, the weight of slope materials and consequently slope stability.

Table 5. 2. External mechanisms for mass movement occurrence. External forces are sourced from the environment and place stress on a slope, causing it to fail (adapted from (Bell, 1999)).

INTERNAL FORCES	
Slope gradient	Topographical controls such as the steepness and height of slopes influences the shear strength of the slope and may determine the type of mass movement that takes place on a slope. Different types of failure will occur once specific critical gradient thresholds have been reached (E. Smith, 2004).
Tectonic stresses	In the process of mountain building, tectonic forces gradually build up stresses within the bedrock and consequently play a major role in the landscape formation of mass movement-prone areas. Shearing and jointing introduce weaknesses to the rock and further decrease slope stability.
Earthquakes	Seismic shaking is one of the chief triggers of mass movements and provide a sudden release of internal stress within the slope, leading to immediate mass movement events in most cases.
Lithology	The geological properties of the rock masses that form the mountains and their susceptibility to weathering are significant controls on the stability of slopes at Arthur's Pass. Specifically, the greywacke making up the Southern Alps is fine-grained, highly sheared and jointed and is very easily weathered (Cave, 1987). These properties combine to form a type of lithology that is able to disintegrate without great difficulty.
Extent of weathering	Water is a powerful agent for the breakdown of rocks, and the Southern Alps are particularly vulnerable to physical and chemical disintegration driven by temperature changes, freeze-thaw action, decaying organic matter and the reaction of water, oxygen and carbon dioxide with slope materials (Duff & Holmes, 1993).
Gravity	Gravity is a constant pressure on slope materials and is not able to be controlled or removed. Factors such as rock type, soil saturation and vegetation place greater weight onto the slope so that gravitational forces are able to dislodge materials and cause the slope to collapse more easily.

Table 5. 3. Internal mechanisms for mass movement occurrence. Internal forces reduce the internal stress of the slope until a critical threshold is reached and the slope fails (adapted from (Bell, 1999)).

It is extremely difficult to reliably determine thresholds for the occurrence of mass movements because of the complexity surrounding their triggering mechanisms (E. Smith, 2004). The high number of internal and external variables makes it necessary to recognise that a multitude of specific slope conditions must exist for slope failures to take place.

5.4 SLIDES

The term landslide can be used to describe a variety of slope processes. Landslides constitute most types of downslope movements that transfer rock and soil components (K. Smith, 2004). They are classified according to variations in their mode of transport and the type of material being transported (Highland, 2004). They vary greatly in size, location, distribution and duration and range from rapid, large-scale rock avalanche-type movements to small-scale slips. Varnes' (1978) differentiated between rotational and translational landslides, but for the purpose of simplifying this hazard assessment they are examined collectively as one type of mass movement.

5.4.1 Landslides and rock avalanches

Landslides are the most common form of mass movement in the Arthur's Pass National Park. Recorded detail on their timing and distribution is limited to reports on the larger, more damaging events and generalised descriptions of widespread damage associated with slides in the region, particularly along the highway corridor. They are seldom reported by users of the park or Department of Conservation rangers unless they are obstructing tracks or are a danger to people using the park. As a result, documentation of all landslide events in the national park is greatly lacking. As with other natural hazards, high severity events involving considerable deformation are very rare, but low magnitude events are recurrent and often persistent. Landslide distribution has historically corresponded closely to the location of active fault traces (Crozier, Deimel, & Simon, 1995).

Rock avalanches have a similar mode of failure to landslides, but their mode of transport is more of a flow than a slide. They consist of a streaming mass of pulverised rock fragments and are caused by the failure of bedrock in competent rocks (Eisbacher & Clague, 1984). Keefer (1984) determined that slopes greater than 150m high and with a gradient in excess of 25° are the most susceptible to rock avalanche failures. Dry rock avalanche debris tends to travel beyond the base of the collapsed area, due to the high speeds generated during the descent of the slope materials, and they can travel kilometres from their original position. Rock avalanches are much rarer than landslides and have a more remote probability of occurrence in the Arthur's Pass township area.

5.4.1.1 Evolution of landslides and rock avalanches

Landslides and rock avalanches are typically initiated by naturally-occurring atmospheric events or seismic shaking. There is a strong positive relationship between rainfall intensity and landslide development. The majority of landslides in the Arthur's Pass National Park are triggered by precipitation and through secondary processes connected to the infiltration of water into mountain surfaces. Slides caused by loading, excavation or deforestation typically only manifest along the highway, where road cuts have interfered with the natural slope environment (Highland, 2004). The consequences of landslides are most likely in the catchment zones, which then move downstream to affect areas proximal to the village. Many of the landslide zones in the Arthur's Pass National Park are distant from heavy traffic and urbanisation, signalling that human activities represent only a minor cause of landslides and mass movements at Arthur's Pass.

There is also a strong positive correlation between the occurrence of earthquakes and landslide formation in a region such as the Arthur's Pass National Park. Keefer (1984) infers that the number of coseismic landslides within a defined area is directly proportional to the magnitude of the earthquake. Palaeoseismic data obtained through studies of earthquakes near Arthur's Pass and the relationships derived from this information estimate that seismic events will have a sizeable impact on the Arthur's Pass region in the future (E. Smith, 2004).

Numerous examples of seismogenic landslides and rock avalanches have been identified in the central Southern Alps that can be used to infer and extrapolate information for future events. More specifically, they may be able to give an indication of the expected size and extent of future failures, their modes of failure, and give particular details about the specific attributes of the slopes on which they form. They can also illustrate what the implications are on sediment supply in the catchment and how the environment may react to the formation of landslide dams. However, whilst the Falling Mountain, Twin Fall Stream and Otira Gorge are all locally occurring rock avalanche deposits, their relevance to the Arthur's Pass village area is lacking because they are all located on the western side of the Main Divide, resulting in huge differences in climate, vegetation and geomorphic conditions. The most relevant example of a debris avalanche close to Arthur's Pass under conditions similar to those seen today is the Crow Valley rock avalanche deposit on the other side of Avalanche Peak, to the west of the township. It is understood to have occurred approximately 6100+/-1580 years ago in which more than 29 million cubic metres of material was displaced (Cave, 1987).

It is likely that previous catastrophic landslide events have been generated on slopes with predisposed rock defects, such as open joints and ridge rent faults (Cave, 1987). Ridge rent faults are common in the national park and are thought to represent the gravitational failure of mountainsides. Beck (1968) disputes that they are solely caused by gravity because the highly-weathered greywacke forming the Southern Alps is resilient enough to withstand the forces of gravity alone. It is suggested that earthquake activity plays an important role in the formation of ridge-rent structures in the Arthur's Pass National Park in tandem with gravitational forces.

It has been demonstrated by Korup (2004) that a perennial supply of landslide debris in alpine catchment areas, such as the Bealey Valley, has been responsible for substantial aggradation and channel avulsion in the past. In the Southern Alps, landslides are the primary source of large quantities of debris into the fluvial system and have the potential to supply catastrophic volumes of sediment into the river (Korup, McSaveney, & Davies, 2004).

5.4.1.2 Landslide dams

In the alpine region of the South Island, landslide dams are regularly forming to alter the natural equilibrium of the mountain environment. Tremors are often responsible for the localised reactivation of slump cracks on mountainsides, leading to potential threats to the river and village in the form of landslide dams (Paterson & Berrill, 1995). Landslide dams are natural barriers of slope debris formed over a water course as a result of a slope collapse. After formation, landslide dams evolve to create serious issues in terms of sediment and water release both upstream and downstream of the dam (Nash, 2003). A very good example of a landslide dam similar to that proposed for the Arthur's Pass area is the Poerua Valley landslide dam formed in 1999 (Hancox & Institute of Geological & Nuclear Sciences Limited, 1999) (Figure 5.2).

Dam formation is greatly dependent on several factors such as the type of landslide and the type of slope materials, the velocity of the landslide, the morphology of the valley and the distribution of landslide debris within the valley floor (Nash, 2003). The factors that determine the longevity of a landslide dam (and consequentially the level of risk it poses) are the size of the landslide and the size of the river that is dammed (Nott, 2006). Dams that are sufficiently large will form permanent dams (Zaruba & Mencl, 1982), but it is plausible that landslide dams stemming from slope collapse within the Bealey Valley are temporary and will eventually be eroded away or undergo sudden collapse. Once formed, a landslide dam is unpredictable and may last several minutes or several thousand years (Schuster, 1993).

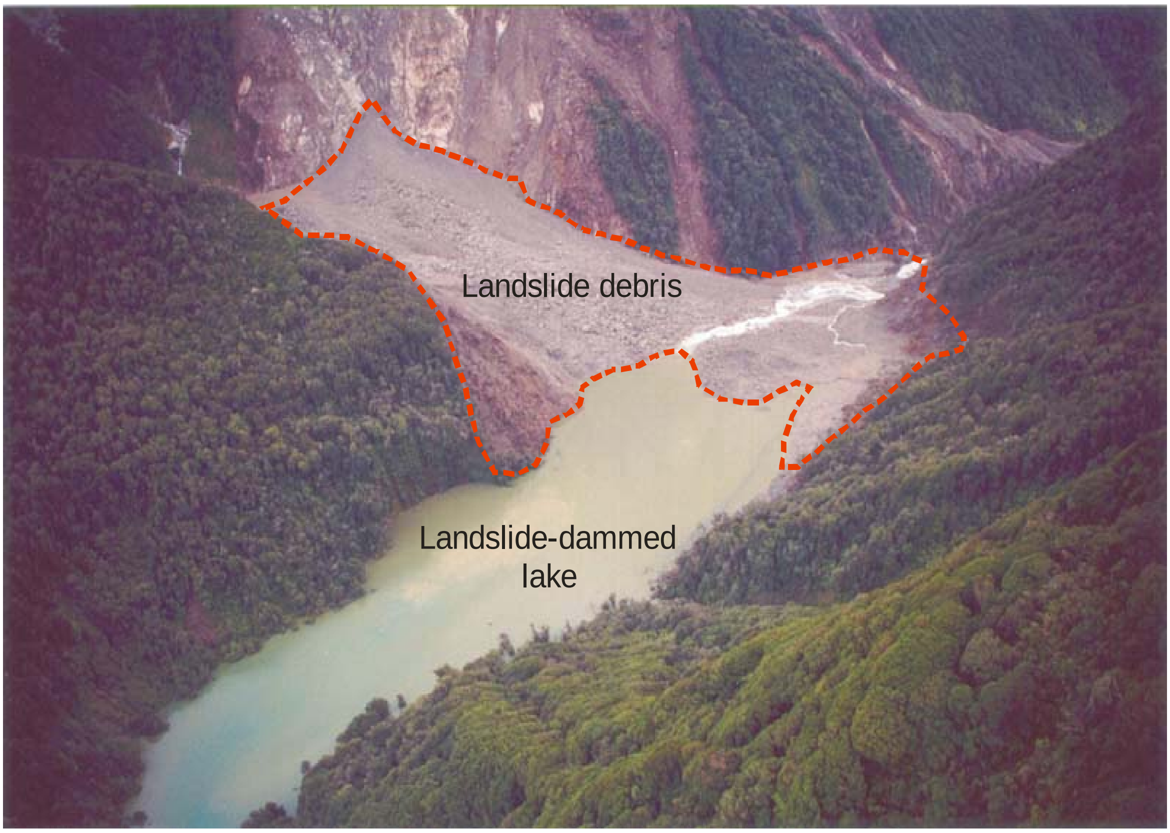

Figure 5. 2. The Poerua Valley landslide dam that formed in 1999, showing a good example of what a landslide dam within the Bealey Valley may look like. Depending on the location of the landslide, the Arthur's Pass village may be submerged by subsequent dam formation (GeoNet, 2000).

There are considerable differences in the outcomes of landslide dams to the Arthur's Pass village depending on whether they occur upstream or downstream:

1. Upstream mountain collapse will dam the Bealey River and release unknown quantities of landslide debris, fluvial sediments and water towards the village. There is also the serious threat of a sudden dam breach, leading to a massive discharge of debris and water which would cause a large-scale natural disaster within the town.
2. Downstream dam development will generate catastrophic flooding and aggradation in areas within a 50 metre elevation of the dam. If the Graham Stream or Halpin Creek areas were to dam, the village would be in a prime location to be destroyed by floodwaters, landslide debris and excess fluvial sediments.

Consequences of the damming of a river also depend on whether the river is partially or completely blocked (Nash, 2003). The hazards associated with landslide formation are typically short-term, and manifest as either sudden, major flooding or gradual, low-impact discharge resulting in less damage. After sampling 73 landslide dams, Costa and Schuster (1988) determined that 85% failed within one year of formation. However, Nash (2003) points out that blockages can last for several thousand years because of their natural stability and resistance to erosive processes. When assessing the overall stability of landslide dams, however, it is clear that in the Southern Alps they have a moderately low resistance to erosion and other sediment and water transport processes (Nash, 2003). Furthermore, whilst erosion of a landslide dam is a typically a gradual process, event-related collapse and short-term consequential hazards may result, forming debris flows, disastrous flood outbursts, backwater pooling, channel instability and fluvial aggradation before the dam and river can return to a state of equilibrium (Korup, 2005).

Most of this analysis assumes a large-scale event along the Bealey River. However, smaller-scale damming is also feasible in the other tributaries that will result in more localised damage. For example, Rough Creek is steep and narrow and moderate volumes of sediments would be sufficient to induce a blockage in the drainage channel. Obstruction in this manner would result in problems on the Rough Creek fan and have negative impacts on the properties situated on the fan.

5.4.2 Minor slips

Minor slips and washouts have been differentiated from larger landslides and rock avalanches because they are much more frequent, they have smaller volumes, and their modes of failure are greatly influenced by artificial or human activities. As a result they may have been responsible for more damage to infrastructure and property in the town, but this damage is not usually catastrophic and is fairly easily fixed with simple remedial treatments. Whitehouse and Griffiths (1983) and Paterson (1996) mapped various slope instabilities along the highway through Arthur’s Pass, although their main focus was on the Otira Gorge section containing the Otira rock avalanche. Their results conclude that the damage along the highway from earthquake-induced slides tends to be site-specific and depends on local topographic factors rather than the distance from the epicentre of the earthquake.

Hundreds, possibly thousands of small slope failures have affected infrastructure along the Arthur’s Pass highway corridor since the establishment of the road through the Southern Alps in 1865. Those blocking the road are promptly cleared, and undermined and washed out sections of road are repaired as soon as is practicable because of the importance of State Highway 73 as an essential transport link between the east and west coasts. Evidence of minor slips is discernible along the entire highway corridor throughout the national park (Figures 5.3 and 5.4). They are easily initiated and are often aggravated by human activities related to road cutting and bridge construction.

Small slips always feature dominantly in post-earthquake or post-storm periods. A number of sites show repeated collapse and have subsequently been reinforced. Examples of mitigated slopes are at White Bridge, north of the village, behind Mountain House Backpackers on the main street of the village and along the McGrath Stream section of road.

Minor slips are chiefly regarded as a nuisance along the highway corridor rather than a serious threat to lives because they tend to be reasonably localised and rarely affect anything other than roads, railways and bridges. They are commonly found obstructing tramping routes but the lack of reported casualties from small-scale slips denotes that they pose a lesser threat to the community than large-scale slides and rockfalls, which have been proven to be deadly on several occasions within the national park.

5.4.3 Subsidence

Subsidence is usually observed in deep alluvial deposits or in limestone terrains that are found in the Canterbury Plains. It is related to the slow dissolution of carbonate rocks by acidic groundwater (Owens et al., 1994). It is also caused by liquefaction from ground shaking and subsidence due to peat drainage in marshlands (Owens et al., 1994).

There have been no recorded incidents in the Bealey Valley despite the presence of limestone caves less than 32km away in the Castle Hill Basin, a low depression bounded by the Craigieburn and Torlesse Ranges (Department of Conservation, 2008). Given the greywacke-dominated lithology of the Arthur’s Pass area, it is possible to surmise that there is an extremely low likelihood of subsidence in the region.

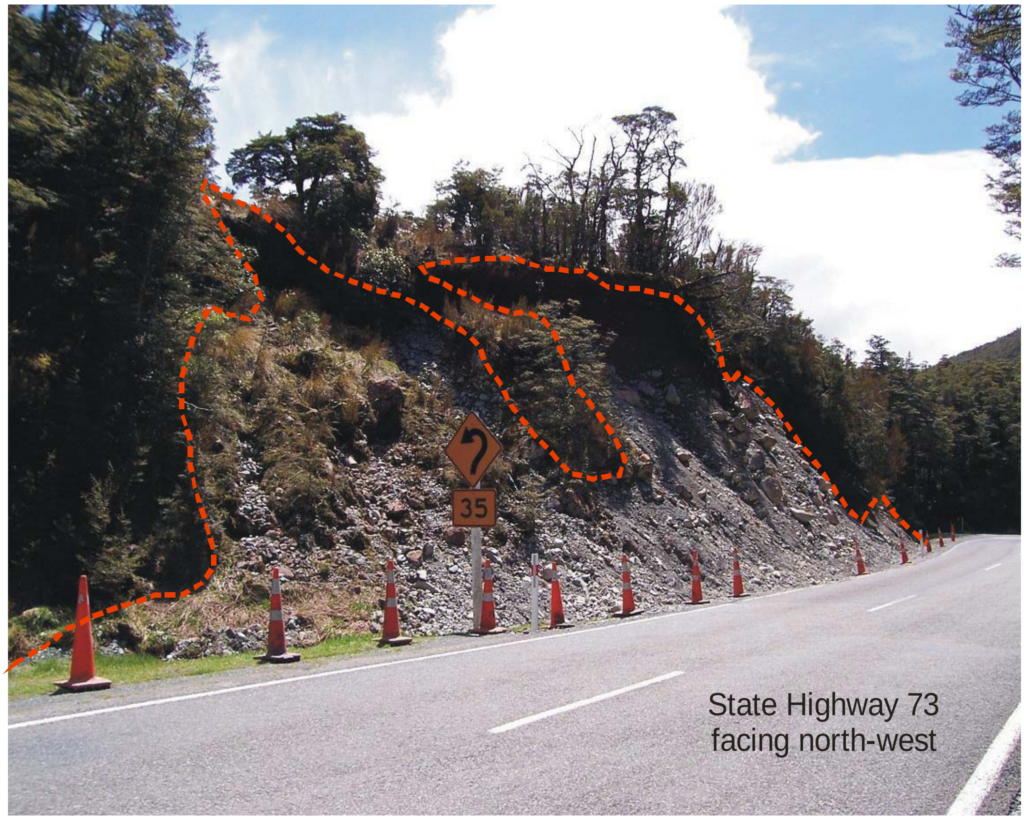

Figure 5. 3. Small-scale slope failures corresponding to man made road cuts along State Highway 73, immediately north of Arthur's Pass village.

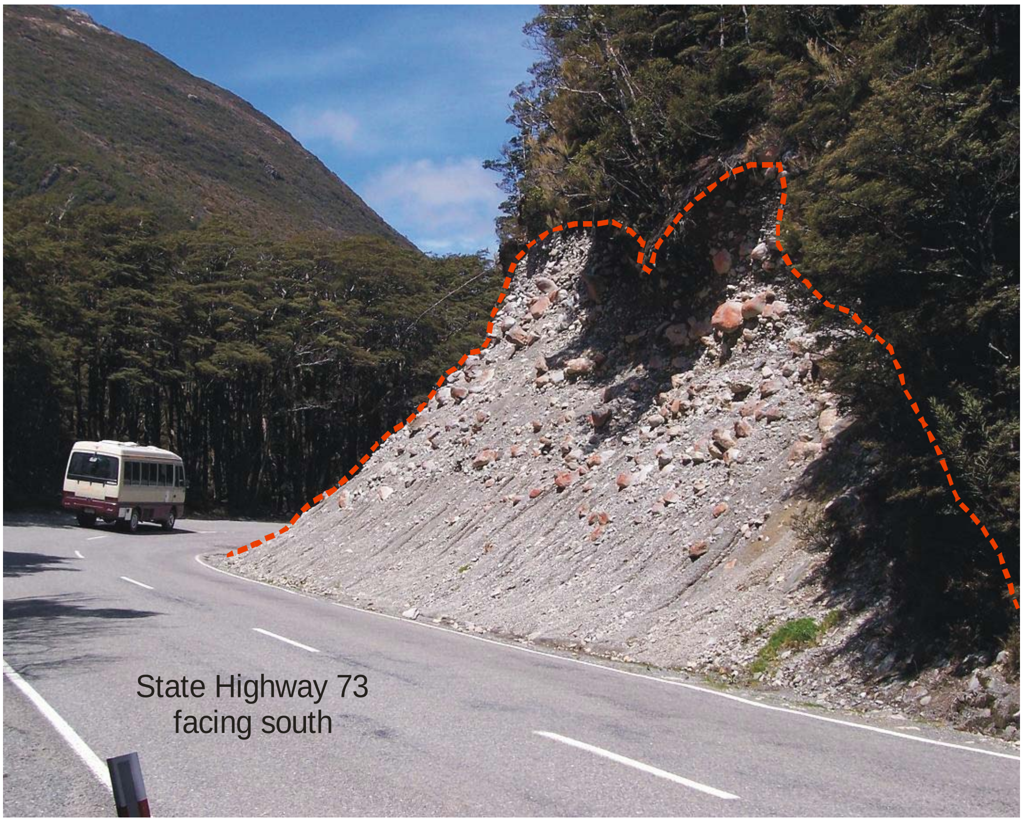

Figure 5. 4. Small-scale slope failures also corresponding to man made road cuts along State Highway 73, immediately north of Arthur's Pass village.

5.5 ROCKFALLS

Rockfalls are comparatively frequent, small deposits comprised of loose bedrock blocks or boulders moving through air with very little interaction between individual rock fragments. In some cases, alluvial material may be included as well. Movement can be in the form of free falling, rolling or saltation and is simply a detachment of rock materials from slopes (Bell, 1999). Frost-thaw action and high intensity rainfall are two of the major causes of rockfalls (Whitehouse & McSaveney, 1992). Other triggers of failure include seismic shaking, wind, thermal changes and stress release (Paterson, 1996). In previous mass movement studies, rockfalls have been found to originate on slopes steeper than 40° (Keefer, 1994).

Individual rockfalls are rarely acknowledged in the literature or on Arthur’s Pass mountain safety websites, but innumerable deposits have been recognised throughout the township area and are judged to be a moderate threat to the community. Although they represent a minor type of mass movement, rockfalls are potentially dangerous to individuals, particularly to trampers and climbers in the National Park. Four people have sustained injuries from rockfalls in the national park since 1998 (Kates, 2008). There are small shingle deposits on the slopes next to most of the major tributaries in the Bealey Valley, particularly along Rough Creek and Punchbowl Creek. The Department of Conservation has installed warning signs below a large rockfall deposit just upstream of the Devils Punchbowl Falls viewing deck (Figures 5.5 and 5.6), and has similar signage advising caution on the Mt. Bealey Track where rockfalls are a major issue.

Keefer (1984) describes rockfalls as the most abundant earthquake-triggered mass movement in New Zealand. They occur primarily in closely jointed, weathered or sheared rock types; a characteristic which is seen in the shattered greywacke bedrock that exists at Arthur’s Pass. Minor rock displacements occur along the highway corridor on an almost daily basis, although the greatest damage from rockfalls is generally in the form of obstructions and damage to the road. However, the number and severity of rockfalls shows a significant increase during storm periods, and there is potential for village properties to incur damage from rockfall deposits in other areas of the village and on tramping routes during calm weather periods (Paterson, 1996).

Figure 5. 5. A Department of Conservation rockfall warning sign located in front of a medium-sized rockfall deposit (Figure 5.6) immediately behind the Devils Punchbowl Falls lookout.

Figure 5. 6. A medium-sized rockfall deposit forming a debris fan behind the Devils Punchbowl Falls lookout. This particular rockfall deposit is in the vicinity of very well-used tramping tracks near the Arthur's Pass village and lies behind the Department of Conservation warning sign (Figure 5.5).

5.6 DEBRIS FLOWS

Debris flows are very rapid, downslope flows formed of water-saturated rock and soil debris. They are typically very dense flows because they have a high sediment concentration, with particle size ranging from very fine sand grains to boulders (Kovach & McGuire, 2003). Flows form when water is added to slope materials either immediately after initial slope failure, or from the mobilisation of previously failed material at a later stage (Grant, 1998).

The advance of a debris flow is highly unsteady and comprises a series of pulses (Eisbacher & Clague, 1984), with the large, heavy materials forming the head of the flow and the fine-grained sediments dispersed towards the tail of the flow (Bell, 1999). They have a density 1.5 to 2 times greater than water because they can be up to 70% solids by weight and they almost always carry some degree of organic material in the form of timber or soil (K. Smith, 2004). Debris floods are classified as halfway between a normal fluvial flood and a material-laden debris flow.

Debris flows are regarded as one of the chief eroding forces in the Southern Alps (Coates & Cox, 2002). They are highly destructive and their flow intensity is ranked according to peak velocity, rather than by their size or extent. Magnitude is determined by the total volume of material transported to the depositional zone during the event and relates little to the original size of the initiating landslide because the bulk of the debris flow material is collected by entrainment whilst the flow is travelling (Jakob & Hungr, 2005). Because they occur most often along minor tributaries, their distribution is to some degree predictable.

There are three major requirements necessary for debris flow formation:

1. <u>Intense or long duration rainfall</u>. Debris flows are fundamentally a precipitation-triggered hazard (Jakob & Hungr, 2005), although the climatic factors influencing their formation have extreme spatial and temporal variability (Wieczorek & Glade, 2005). The ability of slopes to mobilise and form an active debris flow is dependant on atmospheric factors. Sufficient rainfall and snowmelt is required to adequately saturate soils and generate runoff in order to accommodate slope failure.
2. <u>Geomorphic and topographic conditions suitable for debris flow evolution</u>. A narrow, steep gully is more likely to accommodate a debris flow than a wide, gently

sloping river. The flow runout and deposition of debris flows is governed by local topography and the material available for transport along the path of the flow will greatly contribute to its total size.

3. A collapse of surficial slope deposits or bedrock failure in mountainous regions (Eisbacher & Clague, 1984). Progressive failure is rapid in debris flows and there is rarely prior warning that a slope collapse is imminent. Retrogressive slope failure is common along previously weakened slopes (Bell, 1999).

5.6.1 Debris flow deposits at Arthur's Pass

Angular rock fragments enclosed within a fine-grained matrix form the debris deposits in the Arthur's Pass vicinity. They have chiefly been identified within stratigraphic columns comprising alluvial sediments and moraine deposits (observed as a miscellaneous accumulation of rounded pebbles and boulders with sand and clay particles), although it is difficult to categorically associate these deposits with debris flow activity.

Erosional and depositional indicators of debris flow or debris flood activity are seen in the form of exposed tree roots, irregularly leaning trees, incipient embankment failures, sharp trim lines along creeks and scarred vegetation (Eisbacher & Clague, 1984). Several mass movement features have been identified near the village, in the form of debris fans. Graham Stream, Rough Creek, Wardens Creek and McGrath Stream all exhibit traces of debris flow material to some degree. Rough Creek and McGrath Stream may have accommodated heavier debris flow or debris flood activity because they show possible remnants of several debris flow indicators such as leaning trees and trim lines (Welsh, 2007). Outside the stopbanks on the Rough Creek fan are old but very typical debris flow deposits, with hummocky morphology and large angular boulders. Debris flows coming down Rough Creek could potentially travel anywhere over the fan, to houses on either side of Rough Creek.

The most recent record of a debris flow near Arthur's Pass was observed during a storm on the 2-3rd December 1979. During the night, a debris flow initiated in a small gully above the Klondyke Corner campsite (5km south of the village) and killed four campers sleeping in a tent (McSaveney, 1982b). Other than this report and other unconfirmed minor incidents along tramping routes in the Arthur's Pass backcountry, there are no examples of specific debris flow events within the village area in recorded history.

5.6.2 Debris flow identification at Arthur's Pass using the Melton Ratio

Most recently, developments have been made into the recognition of debris flow, debris flood and flood hazards using watershed morphologies. As part of this research, a specific technique has been formulated that examines catchment parameters such as watershed area and topographical relief within the watershed to generate a numerical value called the Melton ratio, which is assigned to each catchment area. The Melton ratio is a value used to differentiate between debris-flow, debris flood and flood prone catchments (Wilford, Sakals, Innes, Sidle, & Bergerud, 2004).

The Melton ratio thresholds dividing debris flows, debris floods and normal floods are:

0.00 – 0.30	Very high likelihood of NORMAL FLOODS Low likelihood of debris flows
0.30 – 0.55	Very high likelihood of DEBRIS FLOODS
>0.55 – 0.60	Very high likelihood of DEBRIS FLOWS

There are inconsistencies in the literature with regard to the assigned thresholds defining each category that are possibly due to the research being in its somewhat preliminary stages. For the purpose of this study, the thresholds used by Welsh (2007) have been applied because his GIS model was used to delineate the debris flow-prone areas for this project. Thresholds may be slightly lower in the South Island because of slightly less perfect environmental conditions and geological dissimilarities compared to the Coromandel, where much of Welsh's (2007) research took place.

This method was applied to every major contributing stream in the Bealey Valley (between the Main Divide and the Bealey/Kowhai confluence), resulting in the classification of ten streams into debris flow-prone or debris flood-prone areas. Of the ten streams studied, none had a ratio index of less than 0.3. All were classified as debris flow-prone streams with the exception of Rough Creek and McGrath Stream, which were calculated to be debris flood-prone (Table 5.4).

TRIBUTARY NAME	RELIEF	WATERSHED AREA (km^2)	MELTON RATIO	WATERSHED LENGTH (km)
Avalanche Creek	1.063	0.896	**1.123**	2.00
Bealey River	1.320	3.913	**0.667**	3.51
Bridal Veil Stream	1.040	1.229	**0.938**	2.21
Graham Stream	1.103	2.085	**0.764**	2.39
McGrath Stream	1.051	3.855	**0.535**	2.99
Punchbowl Creek	1.161	4.251	**0.563**	3.90
Rough Creek	1.071	4.568	**0.501**	3.12
Twin Creek	0.843	0.636	**1.057**	2.74
Upper Twin Creek	1.062	3.114	**0.602**	3.14
Wardens Creek	0.730	0.215	**1.574**	2.19

Table 5. 4. The characteristics of each major tributary within the Bealey Valley. The Melton ration classifies each stream into debris flow or debris flood-prone based on the watershed length and relief.

At this stage is important to note that this technique can only be used to specify the process most likely to take place within a catchment area, in which case it is of course possible for a normal flood to form along a debris flow-prone tributary, for example. However, in such an instance debris flows would have a much higher probability of occurrence than debris floods, according to the Melton ratio theory.

Also, the length of the watershed influences the risk factor of each tributary. If the catchment is short (less than 2.7km long) there is a good chance that a debris flow travelling down the tributary will reach the depositional fan area (or similarly, State Highway 73 in areas where it parallels the Bealey River) and cause damage. Wardens Creek and Graham Stream have some of the shortest watersheds and may be more accommodating to debris flow movement, suggesting they may pose the greatest debris flow risk to the village area.

Without any previous debris flow data on any of the ten studied tributaries it is impossible to give conclusions on the expected probability of debris flows and debris floods in the Bealey Valley. Several debris flow channels can be active simultaneously, which exponentially increases the threat to lives and property (K. Smith, 2004). Despite their speed and range of movement being highly erratic, their recurrence intervals are expected to be long, making the debris flow risk somewhat low. However, if a debris flow or debris flood was to occur, particularly on Wardens Creek, McGrath Stream or Rough Creek, the outcome is likely to be detrimental to the Arthur’s Pass community.

5.7 SOIL CREEP

Soil creep is considered to be an extremely slow form of downslope migration of surficial deposits, usually made up of unconsolidated material and soil overlying bedrock (Eisbacher & Clague, 1984). Soil creep at Arthur's Pass is mostly unrecognised and poorly understood. Because there are very few exposed loess deposits in the area, it is difficult to identify slopes that are undergoing surficial creep. Some localised creep is evident on the terrace slopes along School Terrace and below Brake Hill Road where there is grass cover, but these areas are not considered to represent a significant threat to the village.

Vegetation is widely known to stabilise mountain slopes and reduce the capacity for creep to become established on slopes (Cave, 1987). Using this logic, it is apparent that the Arthur's Pass environment is primarily forested and therefore there is minimal chance of soil creep occurring to such an extent as to signify a serious natural risk.

5.8 IDENTIFIABLE MASS MOVEMENT ACTIVITY AT ARTHUR'S PASS

Comparisons to the Otira section of State Highway 73 indicate that Arthur's Pass is ranked as a lower risk area for landslides, rock avalanches and rockfalls. This does not, however, diminish the notion that there is a very definite risk to the Arthur's Pass community from these hazards. Whilst the number, size and extent of mass movements along the Arthur's Pass section may be lower than the Otira section, the threat is made greater by the fact that there is a dense population of people within the small area that makes up Arthur's Pass. Studying past mass movements give insights into the distribution and timing of future slope failures. Evidence of previous mass movements have been identified predominantly on aerial photographs and as part of field work in the Arthur's Pass region.

5.8.1 McGrath Stream catchment

In the upper reaches of the catchment there is a great deal of sediment already in the stream. There are also countless small-scale slips and landslide scars. Pre-1938 scars have been slightly reactivated and because this cannot be attributed to earthquake activity, they are assumed to be atmospherically-triggered. There are very large landslide marks below the treeline in the upper catchment that formed between 1943 and 1960 (possibly coinciding with the 1946 Lake Coleridge earthquake). This landslide has stabilised by

2007 except for a newly formed, narrow section of landslide debris just above the previous slide. Its location does not conform to any pre-existing stream channels or identified ridges or fault traces.

The Melton ratio for McGrath Stream indicates that it would be susceptible to debris floods more than debris flows. Definite evidence of a specific debris flood event along the tributary is difficult to find, probably because it has been removed by subsequent fluvial processes in the catchment. There is sufficient sediment available within the catchment to supply material for major mass movement events, so it is expected that McGrath Stream constitutes a moderate risk, especially with its location just north of the town.

5.8.2 Punchbowl Creek catchment

Post-1943 there are many bare slopes indicating widespread surficial failure, mostly involving soil and vegetation debris rather than large volumes of rock. A long belt containing large quantities of sediment and debris exists just above Devils Punchbowl Falls, which is releasing material into the fluvial system. Some new, minor slips occurred in the catchment area prior to 1998, which may be associated with the 1994 and 1995 Arthur’s Pass earthquakes.

A large section of the outcrop forming the waterfall sheared off during the 1929 Arthur’s Pass earthquake, depositing large quantities of rock into the tributary. There is also a high risk of smaller rockfalls and topples within the valley. A medium sized scree fan can be found near the Punchbowl Falls lookout, which has a Department of Conservation warning sign. Such scree deposits are common along many of the tramping tracks throughout Arthur’s Pass National Park.

The Punchbowl Creek debris fan at the creek’s confluence with the Bealey River is large and thick and indicates that there is a large quantity of sediment available for the creek to transport. The Melton ratio suggests that Punchbowl Creek would be more susceptible to debris flows, although the morphology of the creek may make it difficult for debris flows to initiate and travel down into the Bealey Valley.

5.8.3 Wardens Creek catchment

At least six pre-1938 landslide deposits are discernable in the Wardens Creek catchment, of which three are large-scale slides. By 2007, they are partially revegetated although the three major landslides are still very obvious. There are fresh scars on the flanks of Avalanche Peak moving into the Wardens Creek channel, and numerous small slips above the treeline that are depositing very large volumes of sediment into the creek. Most of the scars have not reactivated after 1938 which suggests they have stabilised.

Wardens Creek has a moderately-sized debris fan at its mouth and a very high Melton ratio that suggests it would be prone to debris flows. Whilst it is narrow and the flow of water fairly low, Wardens Creek is suggested as another possible high risk debris flow area on account of its steep topography, high sediment availability and the presence of a large debris fan at the creek’s confluence with the Bealey River, although no depositional indicators have been located along the tributary to support this theory.

5.8.4 Avalanche Creek catchment

Avalanche Creek is not a major threat to the Arthur’s Pass village because of its size. Only minor slips and small rockfalls have been identified in the creek catchment since 1938 and therefore, the risk in this area is deemed to be low. There is very little material available at the head of the creek that could become available for transport which also suggests that the debris flow risk in that catchment is very low.

5.8.5 Rough Creek catchment

Rough Creek is likely to be the greatest threat to the village, not only because it is an active tributary with a variety of different hazards but because a large percentage of the village buildings are sited on its debris fan. Throughout the catchment there are sheared cliff faces and slip scars leading down to the tributary (Figure 5.7). There are also very obvious paths of flattened trees where large boulders (up to several metres in diameter) have been dislodged and rolled through the thick vegetation into the riverbed (Figures 5.8 and 5.9) .

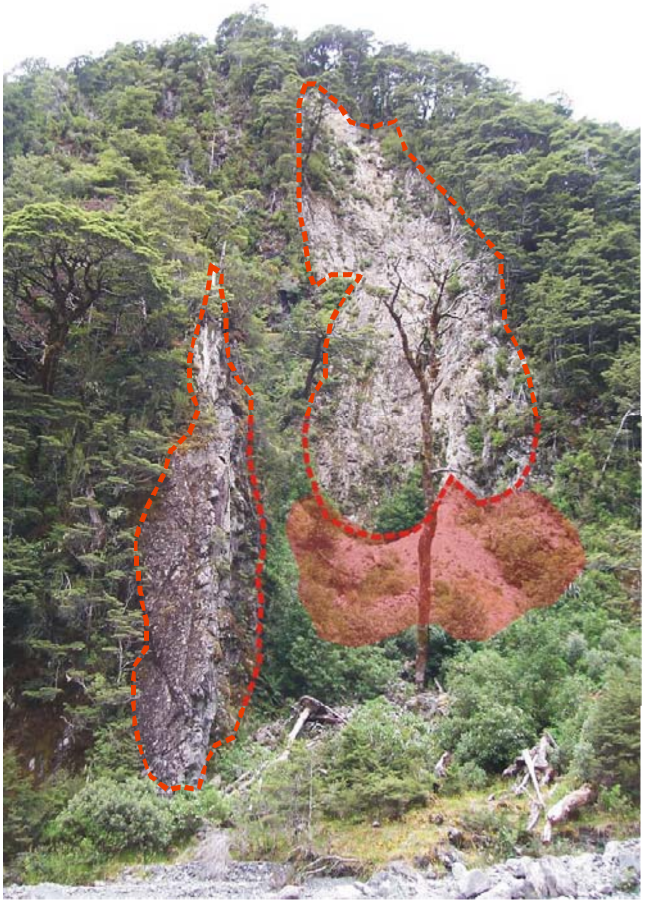

Figure 5. 7. Unstable slopes and cliff faces in the lower Rough Creek catchment. The shaded red area highlights the debris deposit resulting from failure of the right slope.

Figure 5. 8. A path of damaged and flattened vegetation showing the movement of a dislodged boulder down the slope into the Rough Creek tributary.

This tributary contains very high quantities of landslide material, but no new major slips have been identified on the neighbouring slopes between 1938 and 1977. A medium slip appeared in the upper reaches of the creek post-1977 which may be attributed to the 1994 or 1995 Arthur’s Pass earthquake. The Rough Creek catchment is a very dynamic system because there are countless small-scale slope failures in the catchment that are constantly active and do not show signs of revegetation. There are many small, narrow slips on the bank opposite the Rough Creek mouth that formed before 1938 and which correspond to damage sustained during the 1929 Arthur’s Pass earthquake. They are still observable on the slopes in 2007 but have undergone considerable plant regeneration, indicating that they have stabilised (Figure 5.10).

The Melton ratio of Rough Creek was the lowest of the ten streams analysed at Arthur’s Pass, which places it in the debris-flood-prone category. The creek has a steep riverbed, a large quantity of sediments available for remobilisation and an extensive debris fan, suggesting it is very capable of generating debris floods and flows, which could travel to the Bealey River and destroy buildings on the fan. Evidence of more recent debris floods may have been buried or removed by subsequent fluvial processes or covered by foliage.

5.8.6 Graham Stream catchment

The slopes along Graham Stream show extensive landslides, remobilised rock fragments and debris. Some areas have become revegetated by 2007 below the treeline. There is a large protuberance at the mouth of Graham Stream that is more resistant to fluvial processes than the rest of the Bealey River and is potentially a site of future slumping and landslide dam formation across the river. There also appears to be evidence of large-scale slumping previously on the flank of Mt. O’Malley above Graham Stream, which could be an indicator of likely coseismic slope weaknesses in the future, forming a landslide dam. A similar slump feature has been recognised on Mt. Bealey, near Halpin Creek. The Melton ratio for Graham Stream places it in the debris flow-prone category however it is unknown whether the tributary has previously accommodated debris flow events. There is a fairly large debris fan at its mouth but a narrow band of vegetation runs down the centre of the stream near its confluence with the Bealey River, which has remained untouched since the first aerial photos were taken in 1938. This may suggest that the lower reaches of the tributary are fairly stable and more resistant to mass movements than other tributaries in the Bealey Valley.

Figure 5. 9. Very large boulders in the Rough Creek tributary that have been dislodged from adjacent slopes and traversed through alpine vegetation to reach the creek. **A.** is approximately 2m in diameter. **B.** is 4-5m in diameter and has left a path through the vegetation on the northern slope after being dislodged during the 1994 Arthur's Pass earthquake (Figure 5.8).

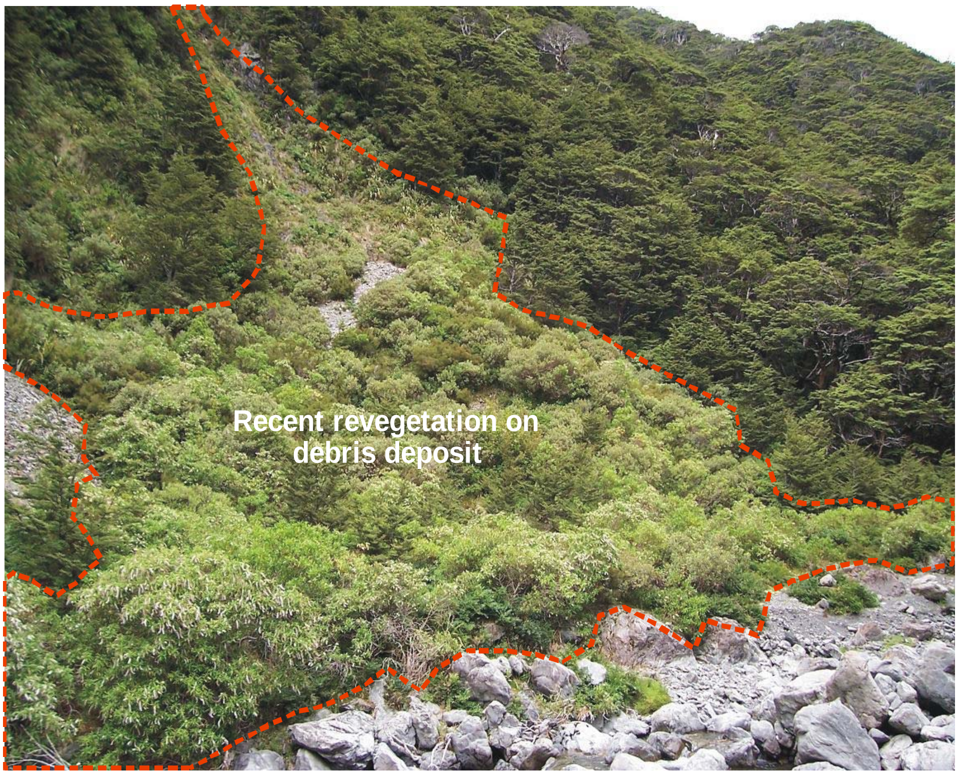

Figure 5. 10. A partially revegetated debris fan in the lower Rough Creek catchment. The stage of revegetation can give an indication of how recently the slope was active.

5.8.7 Other mass movements zones

A medium-sized, elongate landslide has been identified directly behind the houses on School Terrace. It formed before 1938 and was revegetated by 1977. An inspection carried out in the field confirmed that there are no older trees in the area affected by the School Terrace landslide, and that the majority of regrowth is small ferns and shrubs. School Terrace has been identified as a glacial moraine deposit but there is a thin deposit of mass movement material up to one metre thick overlying the moraine deposits. Both deposits are further covered by a thick sheet of loess.

Numerous, recurrent slips along the highway are continuously observed that pose a moderate threat, especially to town infrastructure. South of the village boundaries, there are plenty of possibilities for sediment dumping into the Bealey River from slopes on both sides of the river between Graham Stream and Halpin Creek that will have considerable impacts on the township (Figure 5.11). In the past, shallow sections of Halpin Creek have been buried by gravel during storms (Whitehouse & McSaveney, 1992).

There is a large-scale slope failure downstream of the village between Brett Stream and the bank opposite Halpin Creek. This zone is potentially a major landslide dam threat. It also has a protuberance at its base that shows a similar resistance to fluvial erosion as the Graham Stream protuberance. Additional zones of weakness exist north of the village in several locations adjacent to the highway, particularly along Rome Ridge and Goldney Ridge which may have the capacity to give way and form a landslide dam upstream of the township.

The combination of different mass movement processes at Arthur’s Pass gives rise to complex mountain conditions and provides a number of hazard scenarios. Single landslides can exhibit a variety of downslope velocities, and they may occur in conjunction with other environmental processes to generate complex geomorphic events (Kovach & McGuire, 2003). For example, a landslide may contribute sediments for the formation of a debris flow, during a storm, or a landslide may block the river system and generate flooding and aggradation in the local vicinity of the dam.

Figure 5. 11. Mass movement scars in the Graham Stream catchment (left) and on the slope opposite Halpin Creek (right), viewed from the Rough Creek riverbed. These particular instabilities are constantly active, and have shown only partial revegetation over the last 80 years.

5.9 RELATIONSHIPS BETWEEN MASS MOVEMENTS AND OTHER NATURAL HAZARDS AT ARTHUR'S PASS

Fluvial hazards, atmospheric conditions and mass movements have a very close relationship and often work in unison at Arthur's Pass. Fluvial responses in the Bealey Valley are greatly controlled by precipitation. Sediment generation is a fundamental concern for hazard managers in the Bealey Valley because the fluvial system is more capable of draining excess water if it does not contain suspended sediments. Once sediments are introduced into the system, massive aggradation, increased flood-frequency and large-scale channel avulsion will result (Korup et al., 2004).

By comparing New Zealand to other seismically-active regions, it is possible to deduce that the impact of seismogenic landslides on long-term erosion hazards is significant. Keefer (1994) demonstrated that the Southern Alps have some of the highest rates of erosion from earthquake-triggered mass movements, along with Hawaii, San Francisco Bay and western New Guinea. This illustrates the bearing that slope processes have on fluvial hazards. Alternatively, Crozier (1995) used landslide distributions to analyse palaeoseismicity in the North Island of New Zealand. He concluded that the main requirement for this to be a success is that landslides are correctly identified as seismogenic landslides. Speight (1933) used this technique to locate a new fault rupture after the 1929 Arthur's Pass earthquake. The signature landslide distribution within a narrow strip of area suggested that the landslides were caused by a proximal earthquake source. The fault was later identified by Berryman and Villamor (2004) as being the point of origin of the earthquake.

5.10 PROBABILITY ESTIMATES FOR MASS MOVEMENTS

Mass movements often have a high spatial variability, which can be difficult to translate into a suitable risk assessment. This lowers the likelihood of accurately assessing the mass movement risk at specific Arthur's Pass sites and makes it very difficult to mitigate for these hazards. Furthermore, a lack of definitive landslide data in the national park diminishes the possibility of accurately determining probability estimates. The nature of the national park is such that large events with great significance to a natural hazard analysis may be left unnoticed for an indefinite length of time, and those that are reported are not done so with a high degree of detail, so it is difficult to assess local mass movements using only these criteria.

Without the benefits of an in depth engineering investigation of current slope stability, it is not possible to quantitatively pinpoint which slopes are conclusively the most prone to failure in the future. As with any natural hazard, the aim is not on predicting the exact arrival of an event, but accurately estimating its potential frequency and expected severity so as to assist in the preparedness of communities at risk of disaster.

5.11 MASS MOVEMENT MITIGATION

5.11.1 Methods of slope stabilisation

There are two approaches in the mitigation of mass movement hazards:

- PASSIVE METHODS – These are non-invasive methods and tend to be preventative measures. Passive methods include the practice of effective land use planning and monitoring of the dynamic slope environment for indicators of impending mass movements.

- ACTIVE METHODS – These are invasive methods of mitigation directed towards stabilisation and control of slopes. They are implemented when human infringement on areas susceptible to mass movements pose an unacceptable risk (Eisbacher & Clague, 1984). Examples are the installation of buttresses, chains and cables, anchored mesh nets and rock shelters. Alternatively, stabilisation may be achieved through benching, scaling, trimming and excavation (Jochim & Colorado Geological Survey, 1988).

Physical stabilising practices are typically only practicable on smaller slopes within close proximity to human activities, such as along road cuts and throughout sections of the village. In the case of Arthur's Pass, the size and scale of slopes make it impossible to reliably and cost-effectively mitigate every potentially unstable slope. Hence, the suitability of active mitigation methods is questioned because of the isolated and unpopulous nature of the area, taking into account the moderate to high mass movement risk. High frequency events are less likely to be catastrophically damaging and are more easily prevented and rectified. Whilst the risk of a catastrophic mass movement is very low, there is a very real possibility that it could occur in the next fifty years, so this scenario must be factored into any hazard assessment of Arthur's Pass.

The economic cost of mass movement mitigation measures is a primary consideration when mitigating mass movement hazards. The implementation of a mitigation strategy should cost considerably less than the total value of the property to be protected (Eisbacher & Clague, 1984). However, economic issues may have to be forsaken when human lives are at risk.

5.11.2 Current treatment methods

There are no known monitoring systems currently in place at Arthur's Pass to identify imminent slope failures. It is possible that the cost of maintaining such a system outweighs the benefits because life-threatening mass movement disasters are expected to occur very rarely. The lack of an adequate mass movement warning system in the township is a significant disadvantage and might result in the loss of lives and damage to property that could otherwise have been avoided.

Road builders along State Highway 73 diminish the stability of the slopes by producing road cuts (McSaveney & McSaveney, 1998). The mass movements that occur as a result of human activities greatly contribute to the highway maintenance costs and are responsible for major road reconstruction along several sections of the highway (Paterson, 1996). Consequently, anchored mesh nets, buttresses and retaining walls have been positioned along vulnerable sections of the highway corridor to minimise the risk to road and park users. Road cuts associated with failures between the village and Jack's Hut to the north have also been reengineered in recent years, effectively reducing the potential for mass movement damage along that selected section of highway (E. Smith, 2004).

Gabions have been used in some areas of the village to stabilise smaller slopes. There are up to three stacks of gabions present at ground level behind Arthur's Pass Mountain House backpacker accommodation, which have been supplemented by two fences further upslope to limit rockfalls surrounding the building. These control methods have been in place for a couple of years and during this time have been successful at controlling rockfalls.

5.12 SUMMARY

Mass movement processes at Arthur's Pass are complex and it is clear that they offer significant risks to the local community, road users and individuals within the national park. This mass movement hazard assessment determined that:

1. Slope stability is largely dependent on external and internal slope conditions and mass movement events are more likely to happen in specific terrains that are conducive to slope failure, such as that at Arthur's Pass, which has high rainfall, is seismically active, is within a steep mountainous region and which has a thick covering of loess deposits.
2. Mass movements can be classified according to their initiation mechanisms. Atmospheric-triggered events are the most common, and in the short-term, rainfall is responsible for the vast majority of slope failures. Seismic-triggered events are more prone to generating large-scale mass movements because their probability of occurrence is greater than rainfall-triggered events. Other, slow-moving mass movements are long-term hazards and often go unnoticed. All three occur in the Arthur's Pass region.

3. The incidence of mass movements is heavily reliant on a variety of preconditions and causative factors. Such slope failure factors are both internal and external and include the climatic conditions, soil and vegetation characteristics, weight the slope material, transport agents, slope gradient, lithology and tectonic stresses, gravitational forces and the extent of weathering.
4. Mass movement events can be used to determine the incidence and location of other natural hazards. Landslides and rock avalanches can be examples of indirect evidence for past earthquake shaking and mass movement distributions can correspond to previously unrecognised climatic conditions. Mass movements also have a strong interrelationship with fluvial hazards at Arthur's Pass because they supply and transport slope materials into tributaries within the Bealey Valley.
5. The Melton ratio calculated for ten tributaries within the Bealey Valley indicated that 80% of the streams are debris flow-prone, whilst Rough Creek and McGrath Stream are debris flood-prone. Not all tributaries within the Bealey Valley accommodate debris flows and debris floods. The creeks that show possible debris flow activity in the past (in the form of debris fans or depositional and erosional indictors) are Rough Creek, Wardens Creek, Graham Stream and McGrath Stream.
6. Several zones of slope weakness have been identified within each catchment. The major types of slope instabilities are weathered bedrock failures, surficial loess failures, fault zone failures, failures along road cuts and rockfalls. Rough Creek, Punchbowl Creek and McGrath Stream have the most dynamic catchments because they are steep, have large quantities of sediment available for transfer and display a wide range of previous mass movements such as rockfalls, landslides and debris flows. There is also potential for large-scale landslide damming throughout the Bealey Valley, which would have catastrophic consequences on the village.
7. Probability estimates for various mass movement events are very difficult to determine because of the lack of landslide data and the high spatial variability that they have within a large unpopulated area like the Arthur's Pass National Park. Whilst it may be possible to identify the location of future slope failures, it is almost impossible to determine the expected frequency and severity of these events, so the risk remains high.

CHAPTER 6
FLUVIAL-RELATED HAZARDS

6.1 INTRODUCTION

This chapter is the final of four specific hazard assessment chapters and examines fluvial-related hazards at Arthur's Pass. The Bealey River and its tributary streams are some of the most prominent features of the Arthur's Pass landscape. Accordingly, they are also responsible for some of the most frequent natural hazards in the region. For the last 80 to 100 years humans have lived on the river system at Arthur's Pass, contributing greatly to fluvial-related hazards. River hazards can take the form of surface floods, flash floods and fluvial floods, in addition to erosion and aggradation of sediments in the riverbed. Surface flooding has been discussed as part of the meteorological hazards in Chapter 4, and debris flows are included as part of the mass movement section in Chapter 5.

The objectives of this river-related hazard assessment are:

1. To describe the characteristics of the Arthur's Pass drainage network to better understand the fluvial processes and factors that make the Arthur's Pass area susceptible to river-related natural hazards.
2. To explain the fluvial-related hazards identified at Arthur's Pass, including fluvial flooding, flash floods, channel incision and surface erosion, fluvial aggradation and channel avulsion.
3. To investigate changes to the drainage network within the Bealey Valley over the last 80 years and to document the location, severity and outcomes of past fluvial-related hazards in the Arthur's Pass area with the aim of identifying past issues and potential hazard areas in the future.
4. To describe possible scenarios of flooding, erosion and aggradation and the implications they might have on Arthur's Pass village in the future.
5. To examine mitigation methods for fluvial-related hazards that may be required in the future and describe current methods of river control at Arthur's Pass.

6.2 ANALYTICAL TECHNIQUES

In the case of river-related hazards, fundamental studies of the dynamic river system are achievable using several wide-ranging methods. Investigations relating to aggradation and erosion are greatly supported by reconnaissance carried out in the field because the rivers and streams being examined are, for the most part, easily accessible on foot. From November 2006 to early 2008, the subtle, yet important, geomorphic changes occurring along the Bealey River and its local tributaries were monitored to gauge the response of the fluvial system to various influences such as rainstorms, snowmelt, slope failures and human activities.

The changes identifiable on aerial photographs spanning several decades are equally critical. Photographs from 1938, 1943, 1960, 1977 and 1998, and 2007 satellite images extracted from Google Earth capture transformations made by the Bealey River system over time and give a sound insight into the geomorphic processes working at Arthur's Pass. The 1977 and 1998 images offer limited information because they are high altitude photographs and do not show the village in specific detail.

Examining the vegetation along the Bealey River and its tributaries is particularly important for interpreting zones of recent activity and highlighting areas that have become stabilised and are therefore less liable to changes in the foreseeable future. Study of the interrelationships between plant cover, fluvial processes and the landscape has been completed using remote sensing methods and data obtained from in-field interpretations throughout the year.

Several reports and journal articles provide historical evidence on individual flooding events and the consequences they have on town infrastructure and community safety. This allows for assumptions to be made on the potential location, timing and severity of future events at Arthur's Pass. In addition, correspondence with several of the local residents affords the opportunity to understand the flooding issues from a community perspective and provides vital information on specific incidents and recurring issues that are not able to be sourced from the literature.

6.3 THE ARTHUR'S PASS DRAINAGE NETWORK

The Waimakariri River catchments are characterised by broader and flatter valleys than their west coast counterparts and are dominated by shingle alluvial sediments (Cowie, 1957). Since the cessation of the most recent glaciations, the Bealey Valley has been heavily modified by fluvial erosion and aggradation processes (McSaveney, 1982b). The lower reaches of the Bealey Valley are heavily dissected by fluvial channels (Figure 6.1). The Bealey River is sourced from the Goldney Glacier on Mt. Rolleston and acts as the chief water course through the area. It transports all water and shifting sediments from the local tributaries to the Waimakariri River further south (McCallum, Lovis, Cowie, Glennie, & Mason, 1986). Local streams contributing directly to the Bealey River in the vicinity of the township include Rough Creek, McGrath Stream, Avalanche Creek, Graham Stream, Punchbowl Creek, Bridal Veil Creek and Wardens Creek (Table 6.1).

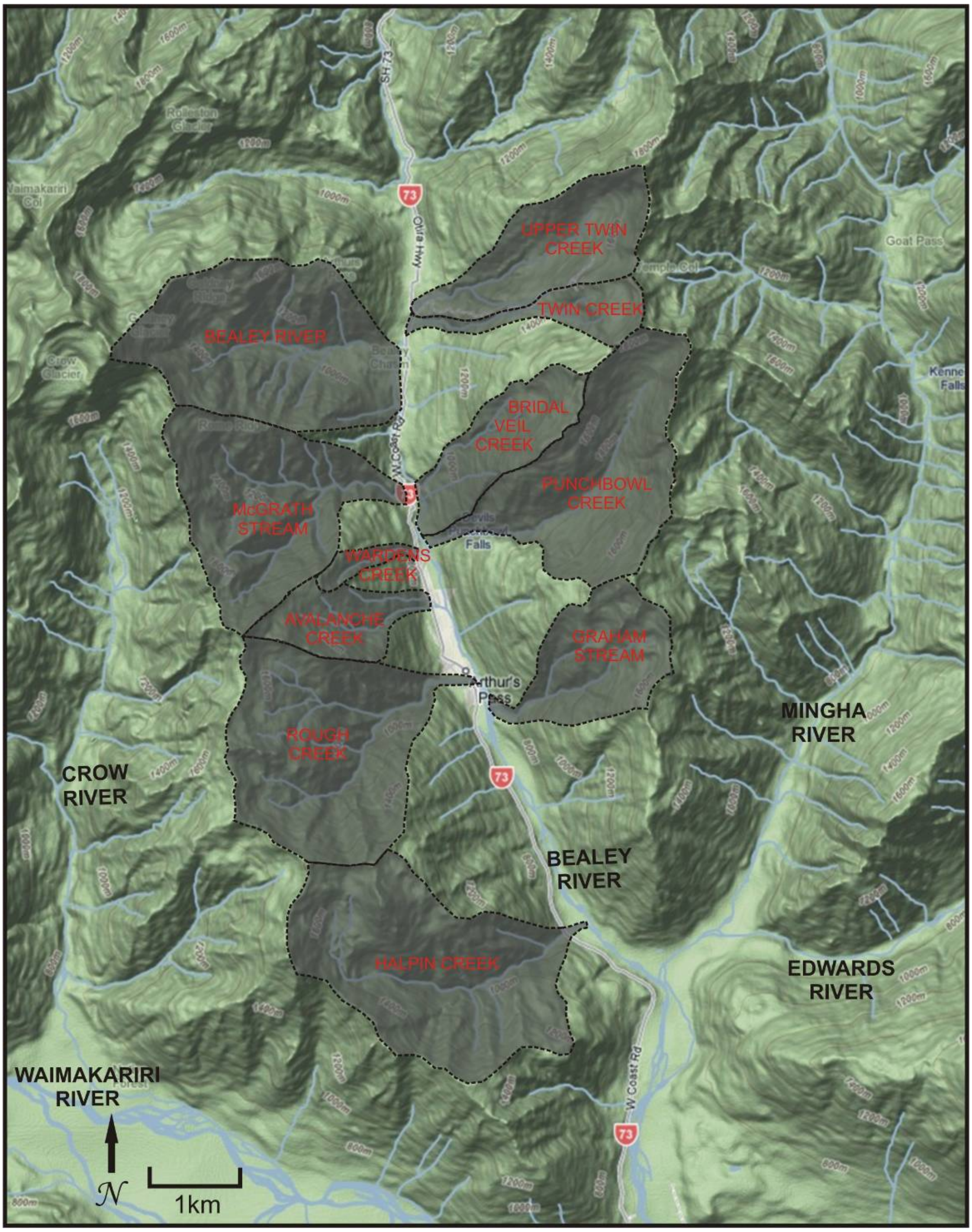

Figure 6. 1. The major catchments in the Bealey River contributing to fluvial-related hazards at Arthur's Pass (map sourced from (GoogleMaps 2008)).

Tributary Name	*Location of confluence with Bealey River*	*Flow attributes*	*Distinguishing characteristics*
Bridal Veil Creek	1.4km north of the DOC Visitor Centre, just north of town boundaries on eastern side of valley.	- Medium flow rate - Moderate depth (0.5-1.0m) - Moderate width - Moderate erosive capabilities	• Steep riverbed gradient. • Two waterfalls (60m and 108m). • Moderately confined channel, particularly in lower reaches.
McGrath Stream	1.3km north of the DOC Visitor Centre, outside of town boundaries on western side of valley.	- Medium to fast flow rate - Moderate depth (0.5-1.0m) - Moderate to wide width - Moderate to high erosive capabilities	• Steep riverbed gradient with both large boulders and fine-grained sediments. • Noticeable channel incision along the riverbanks.
Punchbowl Creek	0.9km north of the DOC Visitor Centre, directly north of numerous dwellings on eastern side of valley.	- Fast flow rate - Moderate to high depth (>0.5m) - Moderate width - Moderate to high erosive capabilities	• Very steep riverbed gradient. • Has produced a very large alluvial fan at the Bealey River confluence. • Devils Punchbowl waterfall (131m) a short distance upstream. • Largely confined by steep rock walls and vegetation.
Wardens Creek	0.9km north of the DOC Visitor Centre, on western side of valley, directly opposite Punchbowl Creek confluence.	- Slow flow rate - Shallow depth (<0.5m) - Narrow width - Low erosive capabilities	• Very steep riverbed gradient. • Channel largely confined by thick vegetation. • Mostly comprised of moderate sized boulders. • Has produced a small debris fan but does not have a high flow of water through it.
Avalanche Creek	0.2km north of the DOC Visitor Centre, between the chapel and the outdoor education centre on western side of valley.	- Slow flow rate - Shallow depth (<0.5m) - Narrow width - Minimal erosive capabilities	• Very steep riverbed gradient with numerous small waterfalls. • Flows under a small road bridge in the centre of town. • Source of the town's water supply, through a gravity-fed filter system. • Largely confined in hillslope areas by thick vegetation.
Rough Creek	0.9km south of the DOC Visitor Centre, adjacent to the Arthur's Pass Police Station and surrounded by numerous dwellings. Flowing down western side of valley.	- Slow to medium flow rate - Shallow to moderate depth (<1.0m) - Wide width - Moderate to high erosive capabilities	• Bedload is mostly comprised of large debris boulders along the whole length of the creek. • Flow is variable and fluctuates greatly with rainfall and season. • Has produced a very large debris fan on which numerous houses have been built. • Contains huge boulders deposited during and after major earthquakes in the area. • Controlled by stopbanks. • No evidence of erosion on opposite bank of river mouth. • Gets its name from the boulders that would flow down the creek during floods.
Graham Stream	1.2km south of the DOC Visitor Centre, immediately south of town boundaries on eastern side of valley.	- Medium to fast flow rate - Moderate depth - Wide width - Moderate to high erosive capabilities	• Very steep riverbed gradient. • Has produced a thick alluvial fan at the confluence with the Bealey River. • Incision of the opposite riverbank where it meets the Bealey River, producing a wide floodplain.

Table 6. 1. The location and characteristics of all major tributaries within the Bealey Valley. All distances are referenced to the Department of Conservation Visitor Centre, located in the centre of the village on State Highway 73.

The smaller, unnamed creeks and gullies that feed the larger streams within the very large catchment area are also significant contributors to the catchment. Within the alpine environment at Arthur's Pass, the steep topography acts as a funnel for surface runoff into the narrow tributaries of the Bealey River catchment (McCallum et al., 1986). The river and the majority of its tributaries are covered by deep alluvial sediments and the formation of alluvial fan deposits at the confluence of tributaries is common (McSaveney, 1982b). The alluvial fans are often the primary source of material for sediment transfer during periods of peak water flow.

There are a multitude of factors that make the Bealey Valley particularly susceptible to flooding in the Arthur's Pass district.

1. <u>The large size of the catchment area</u>

   For the purpose of this study, the Bealey catchment has been divided into two sections; the upper Bealey catchment in which all water and sediment transport takes place through or very close to the village area, and the lower Bealey catchment further downstream, in which river processes are not likely to affect the village. The upper catchment is approximately 44.8km^2 and the lower catchment 16.8km^2. All runoff within the catchment is diverted to the Bealey River, leaving the village in a prime location for damage. When put into context, the Bealey catchment alone makes up about 1% of the total Waimakariri River catchment area (McCallum et al., 1986).
2. <u>Climatic conditions</u>

   Arthur's Pass is exposed to high-intensity and long-duration rainstorms several times each year, causing flood-related issues in the Bealey Valley. There is a direct relationship between the size of the watershed and the duration and intensity of rainfall in producing flood conditions (Wohl, 2000). Snowmelt is another major cause of flooding, particularly during warm periods or after a large snowfall. The contribution of snow melt is often delayed until the summer months.
3. <u>Lack of adequate storage facilities for excess water</u>

   There are no natural or man-made storage areas such as lakes or artificial reservoirs within the Bealey catchment that can accommodate large volumes of water. The mountains provide temporary water storage but are not suitable for collecting large volumes of water (Wohl, 2000).

4. Constraints placed on the floodplain by the village

   Development on the floodplain has rendered a large proportion of the area unavailable to the active river, which does not allow for natural channel avulsion or overflow of water to take place in the area now occupied by the village. Hence, flooding will continue to threaten the town area as long as there is insufficient space for natural channel widening.

6.4 HAZARDS LINKED WITH THE FLUVIAL SYSTEM AT ARTHUR'S PASS

Flooding and river sediment transport processes are similar, because they are the product of very similar mechanisms. The difference is that they take place over separate time scales; floods develop relatively quickly, typically occurring minutes to days after the triggering event. Erosion and aggradation may be exacerbated by flooding events, but ultimately these sediment transport processes take place over a much longer period of time, usually weeks to years.

6.4.1 Fluvial flooding

Floods are the most recurrent and costly environmental hazard in New Zealand, although they tend to threaten property more than lives in the case of Arthur's Pass (Salinger, 1998). Flooding occurs at Arthur's Pass when the volume of water available within the Bealey River catchment exceeds the total capacity of the rivers and streams within the catchment (Wohl, 2000). Encroachment onto the floodplain by the village exaggerates the natural fluvial processes and creates a continuous threat to the community (Australian Water Resources Council, 1985). The floodplain is expected to make adjustments both in the short-term and long-term to accommodate variable flood discharges, causing the morphology of the floodplain to change accordingly (Bell, 1999). Only rarely are the floods within the village severe enough to cause loss of life; the principal issue lies with property damage, temporary loss of amenities and the consumption of valuable emergency resources.

Analysis of the rainfall records of the past 50 years indicates floods do not follow any seasonal patterns. However, the effects of snow melt as a contributor to river flooding are typically seen with the onset of the warmer months. This is especially evident after a winter season with very heavy snowfalls. Often there is a delayed influx of water because the temporary snow accumulations require warm conditions to melt the thick snow packs (K. Smith, 2004).

6.4.1.1 Flash floods

Flash floods form rapidly with little or no advance warning, often in areas with steep terrain. They typically develop as a result of intense rainfall and are often characterised by high flow velocities (Kovach & McGuire, 2003). Flash floods are particularly common in the Bealey River and tend to occur every few months during heavy rain periods.

In terms of flash flood occurrence and severity, the most important consideration is not the size and capacity of the fluvial channel but the difference between the peak floodwater discharge and the average annual discharge (McCallum et al., 1986). With its large catchment area, the water level in the Bealey River has the potential to rise rapidly during periods of heavy rain. Consequently, water flow in the streams can rise to a critical level in a short amount of time, catching many people unaware.

Flash floods have a time scale of several seconds to several hours and occur with little or no warning. They have very high flow velocities and may generate a rapid rise in water levels, targeting the village site. Small streams in particular have an elevated risk of flash flooding if they exist within a steep area with thin soil cover and intense local rainfall, producing ideal conditions for the production of flash floods (McCallum et al., 1986).

6.4.2 Channel incision and surface erosion

At Arthur’s Pass, erosion is synonymous with the widespread, continuous depletion of natural gravel materials and soil by water, wind or ice (Kovach & McGuire, 2003). Channel incision relates to the removal of fill material in the Bealey Valley tributaries by the flow of water (Figure 6.2). This creates localised erosion that results in the deepening, widening or flattening of the riverbed (K. Smith, 2004).

River erosion is a long-term hazard and is liable for the degradation of slope stability and protective embankments along the river. There are several causes of erosion in the Bealey River at Arthur’s Pass. By far the most dominant of these is precipitation. Extended wet periods saturate the soil and increase surface runoff within the Bealey River catchment, whilst increased river levels increase the turbulence and sediment transport capabilities of the river (McCallum et al., 1986). Secondary processes contributing to the sediment yield of the Bealey Valley and the severity of erosion rates are:

GEOLOGY –	At Arthur's Pass, the bedrock is highly weathered and fractured greywacke which is prone to shearing, reducing the level of energy required for erosion to occur.
RELIEF –	Slopes over 50° are common in the valley. Slope gradient controls the velocity of surface runoff, thereby lowering the energy required for erosion to occur by reducing the failure threshold of the soil.
VEGETATION –	Below tree line, very dense beech forest exists within the valley. Vegetation reduces erosion by anchoring soil particles on slopes and absorbing water, therefore reducing runoff.
SOIL -	Thin soils with a high saturation rate occur on the slopes near the village. The degree of erosion on slopes is dependent on soil characteristics such as the grain size, bulk soil density and the friction coefficient of the soil (Liu, Chen, & Li, 2001).

Both erosional and depositional processes are easily identified at lower elevations because they form well-defined marks in the vegetation cover. Stable areas show revegetation and unstable areas exhibit scars due to recent activity. Channel incision at Arthur's Pass is present as downcutting of the alluvial fans, scouring of stream banks and where impediments such as bridge supports form obstructions which increase the flow turbulence and aid in erosional processes. Erosion resulting directly from human activities is almost imperceptible within the Arthur's Pass National Park, except on road and trail areas.

Surface runoff is one of the leading causes of erosion, but it is limited on the mountain slopes because infiltration rates are high, and the abundant vegetation acts as a deterrent and slows down or reduces surface runoff (Wohl, 2000). Erosive processes are dominantly confined to the open floodplain area, where vegetation is sparse. Additionally, urbanisation plays a role in the severity of surface runoff and subsequently erosion within the town, especially if man-made stormwater drainage outlets fail to cope with high water levels.

6.4.3 Fluvial aggradation

Aggradation of the river system is defined in this hazard assessment as the modification of a rivers' natural gradient through the increased deposition and accumulation of sediments

(Kovach & McGuire, 2003). It typically follows major storm activity and is the product of sediment transport by external agents such as air, water or ice utilising gravitational forces. Bell (1999) suggests that the floodplain is essentially a sediment storage area which remains in equilibrium except during periods of dramatic, short-term change. Aggradation is a temporary process and signifies that the river is out of equilibrium. Erosion and aggradation processes work in unison; the environment has to be stripped of sediment through erosional processes in order to supply the particles for sedimentation. Similarly, they work on the same time scale because they are controlled by the same environmental parameters such as climate, geomorphology, geology and vegetation.

The numerous alluvial fans observed in the Bealey Valley tributaries are good examples of aggradational deposits (Figure 6.3). They are vulnerable to downcutting, which increases the sediment supply elsewhere in the fluvial system, and oversteepening, which reduces the availability of material downstream. Oversteepening may result in the sudden collapse of aggradational deposits and cause a considerable change in river geomorphology downstream of the slope failure (Wohl, 2000). Vertical accretion in the alluvial fans is most predominant during and immediately after floods when sediment loads in the river are at their highest (Bell, 1999).

6.4.4 Channel avulsion

Shifting channels can seriously threaten communities and Arthur’s Pass is no exception. The floodplain is approximately 300m wide and can accommodate a certain degree of channel shifting within the active riverbed, but long-term redirection of the river which could directly affect the central township area may persist, especially if radical or inappropriate human activities occur. Avulsion is a partial contributor to the flood risk because it affects the proximity of the river to people and properties. However, the movement of channels within the floodplain is moderated by stopbank placement and it is envisaged that protection works primarily aimed at reducing flood damage have thus far effectively mitigated the hazards posed by channel avulsion at Arthur’s Pass. However, a large sediment input may have the capability to easily overwhelm the banks in the future.

Figure 6. 2. Erosion and downcutting of the thick Punchbowl Creek alluvial fan at its confluence with the Bealey River.

Figure 6. 3. The extent of the Punchbowl Creek alluvial fan showing an example of one of the largest aggradational deposits in the Bealey Valley.

The Bealey River is known to have avulsed a number of times in the past several decades, often placing greater strain on the roads and railway at the town site. In many cases the changes are gradual, but sudden flash floods may temporarily and suddenly shift the active channel to cope with the high volumes of water and sediment flowing through the catchment area.

6.5 GEOMORPHIC CHANGES TO THE DRAINAGE NETWORK SINCE 1938

Modifications in the landscape from fluvial processes over the last 80 years are useful indicators of processes that can be expected in the future. Most notably, changes that take place over several years can have detrimental effects on the village and can signal areas requiring further monitoring. The Bealey River is the biggest tributary in the catchment and is the most susceptible to large-scale fluvial modifications. Its position on the wide, open floodplain makes any geomorphic changes more easily discernable from aerial photographs and permits in-field inspections along the Bealey River to be done.

6.5.1 The Bealey River

Most changes to the Bealey River along the village bounds occur at sites of convergence between major contributing tributaries in the valley. Overall, the river has undergone major channel avulsion over several decades and is sensitive to changes brought about by man-made structural modifications of the floodplain, such as roads, railways and housing developments (Figure 6.4).

The active floodplain area is very wide at the northern end of the village. It narrows slightly at the rail bridge before expanding further downstream. At the Rough Creek mouth the Bealey River becomes partially restricted by the Rough Creek fan, which is possibly made worse by the rail bridge that crosses the river at the site. Major channel avulsion has taken place on the wide floodplain where Graham Stream meets the river, and erosion and downcutting of the opposite bank of the floodplain and the alluvial fan have been observed periodically in the area. Similarly, downcutting of the Punchbowl Creek fan is a continuous process. Rough Creek does not appear to greatly influence the movement or location of the Bealey River at its confluence and apart from a small slip observed in the earlier photographs, there is no evidence that the incoming tributary has contributed to scour of the opposite Bealey River bank.

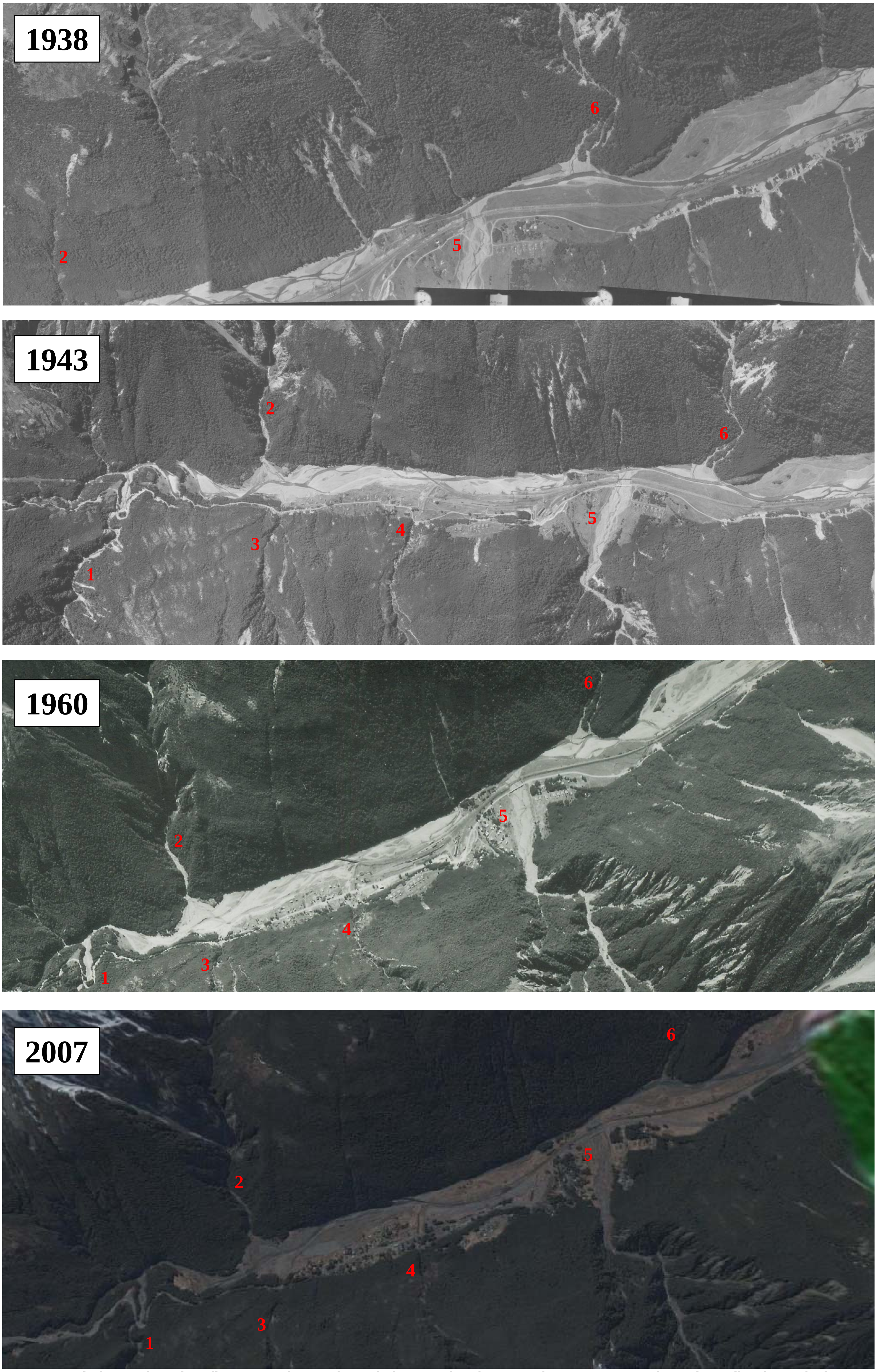

Figure 6. 4. Aerial photographs and satellite images showing the gradual geomorphic changes to the river system in the Bealey Valley during the last 80 years. **1.** McGrath Stream. **2.** Punchbowl Creek. **3.** Wardens Creek. **4.** Avalanche Creek. **5.** Rough Creek. **6.** Graham Stream.

The bridge supports in the Bealey River reduce its carrying capacity to a small degree, because they constrict the movement of water through the river. Therefore, flooding can be more severe at the Rough Creek confluence, which is the narrowest point of the river. Three bridges are located in this area and there is little room for the water flow to traverse the floodplain.

It is uncertain when the stopbanks were installed on the banks of the Bealey River and Rough Creek. By 1960, the main branch of the Bealey River flowed dangerously close to town properties, on the very near side of the active floodplain, and the stopbanks may have been a response to that encroachment. In later years, aggradational processes have been identified the same area near the opening to the Otira Tunnel, which has more recently been subject to scouring.

The braided channels of the Bealey River observed in the 1960 aerial photographs had merged into one channel by 2007. Revegetation has begun on the area of floodplain left abandoned by this process, behind the railway station. Other sites along the river have either remained unaltered or have undergone geomorphic changes that are indiscernible from the aerial images.

6.5.2 Tributaries in the Bealey Valley

The bulk of this section was completed using remote sensing methods, in particular aerial photographs and satellite image analysis. These methods are by no means exhaustive and have multiple limitations. They are often dependent on image quality, scale and timing; the time gaps between sets of images are large enough to allow important geomorphic changes to be unrecorded. Also, variations in the images brought about by the effects of shadow, snow and season can alter the perceptions of certain areas. The 1977 and 1998 photographs were of limited use in this tributary analysis because of poor picture quality and the high altitude from which they were taken, which minimised the amount of detail available.

The perceptible morphological changes along the Bealey Valley tributaries over the last 80 years are widespread (Table 6.2).

Time Period	Rough Creek
1938-1943	• Minimal identifiable change in the tributary and vegetation cover. • There is a small, hook-shaped slip on the slope opposite to the river mouth which has produced a small fan and which is contributing sediments to the Bealey River. • The road bridge was not in existence yet and a diagonal track passes through the river upstream of the current road bridge. • There is some widening of the active riverbed at the railway bridge due to erosional processes operating on the north bank.
1943-1960	• Beginning of development of depositional bank approximately 300-400m upstream of river mouth, on south side of tributary. • Hook-shaped slip has been revegetated and the fan has stabilised and been overtaken by plant cover. • Stopbanks have been positioned on the northern bank of the creek. • A large sediment terrace-like feature has been identified on the northern bank approximately 200m upstream of the rail bridge. It is approximately 200m long and 50m wide. • No significant changes can be observed in the vegetation cover.
1960-1977	• Stabilisation and partial revegetation of depositional bank on the northern bank of the creek. • No discernable changes to active river processes or vegetation cover.
1977-1998	• Increase in building development on northern side of Rough Creek fan. • Some narrowing of channel in the lower 500m of the creek. • Formation of a large aggradational bank on the southern side of the river approximately 300-400m upstream from the rail bridge, sized approximately 150m long by 50m wide. • Installation of stopbanks on the southern side of the creek. • Vegetation largely unchanged.
1998-2007	• Some housing areas on the northern side of alluvial fan remain revegetated. Revegetation has occurred on other areas on the fan, however. • Small hook-shaped slip and resultant fan is completely concealed and stabilised by vegetation.

Time Period	McGrath Stream
1938-1943	• Several small slips have been observed that may be contributing sediments to the river, with some scars becoming reactivated, showing a reduction in vegetation cover. • Channel widening approximately 50-100m upstream from the road bridge.
1943-1960	• Restabilisation of scars on slopes, showing a reduction in sediment input. • Plant regrowth between the road bridge and river mouth on both sides of the stream.
1960-1977	• Noticeable loss of vegetation inside the loop formed by the road. • The active channel widens slightly when it reaches the Bealey River confluence.
1977-1998	• Regeneration of the channel between the road bridge and the river mouth. • Channel narrowing in the same area.
1998-2007	• Channel avulsion is evident along the lower reaches of the stream. • There is a change in the regrowth pattern downstream of the road bridge due to aggradation of the stream. • The sediments in the riverbed spread out before they reach the town, which appears to have prevented aggradation within the village area.

Time Period	Punchbowl Creek
1938-1943	• Northern half of alluvial fan is partially revegetated.
1943-1960	• Small patch of new plant cover is observable on the northern toe of the fan. • Minimal change in the geomorphology of the river.
1960-1977	• Small slip scar near Devils Punchbowl Falls. • No other discernable changes in the vegetation of active riverbed.
1977-1998	• Alluvial fan attributes remain unchanged. • Slips evident in the 1977 photos are stabilising by 1998.
1998-2007	• Fan head still active, has split into two channels, with significant downcutting to the fan toe.

Time Period	**Graham Stream**
1938-1943	• Channel avulsion occurring on the alluvial fan at the mouth of the stream. • Small scars on edge of tributary have started to revegetate. • Scouring on opposite river bank, causing Bealey River to shift.
1943-1960	• Aggradation at mouth of stream and on opposite bank. • Major avulsion and initiation of braiding along the Bealey River at the Graham Stream confluence. • Large scars on slopes upstream have started to stabilise. • Some scour of the fan toe by the Bealey River.
1960-1977	• Minor channel avulsion of the Bealey River along the fan toe. • No major changes to the vegetation along the stream.
1977-1998	• Small aggradational patch on the fan. • No other changes discernable.
1998-2007	• Several areas on the fan have only a light covering of tussock grass, suggesting they have been active in the last few years. • There is evidence of a remnant braided channel along western edge of active channel. • Active channel of the Bealey River is now pushed up against the fan, causing some erosion of the fan deposits.

Time Period	**Wardens Creek and Avalanche Creek**
1938-1943	• Wardens Creek shows some minor slips supplying sediments and aiding alluvial fan development. • Avalanche Creek has undergone minor revegetation and minor stream avulsion. • There is an increase in the housing on the banks of Avalanche Creek downstream of the main road. Main road is over Glasgow Bridge (behind current site of chapel).
1943-1960	• Wardens Creek appears stable, with no discernable changes evident. • New road bridge formed along highway. • Large-scale erosion of the floodplain on the northern side of the Avalanche Creek/Bealey River confluence, immediately north of the railway bridge. • A small scoured patch is observable just downstream of the new road bridge. • Housing development increasing around Avalanche Creek.
1960-1977	• Some regrowth and stabilisation on Wardens Creek fan. • No other significant changes.
1977-1998	• Reactivation of a small, southern section of the Wardens Creek fan. • Avalanche Creek appears unchanged.
1998-2007	• Wardens Creek shows a slight pattern of downcutting at the site of the road. • The active channel has shifted and narrowed. • Avalanche Creek has stabilised and the channel has narrowed. • There is a large quantity of sediment accumulated near where the rail bridge and Avalanche Creek meet, resulting in a steepening of the riverbed at the site. • Avalanche Creek is surrounded by fairly dense housing and is partially revegetated. It has very little impact on river hazards and sediment deposition.

Table 6. 2. Perceptible geomorphic changes along the major tributaries within the Bealey Valley during specific time periods.

6.6 PAST OCCURRENCES OF FLOOD-RELATED DAMAGE

Several times a year the river receives enough rainfall and snowmelt to raise the river at Arthur’s Pass to a critical level. The majority of these cases do not develop into damage-causing floods or erosion in the town. In rare instances, the combination of high rainfall, saturated soils, predetermined elevated river levels, slope gradient and geological factors provide ideal conditions for flood generation and sediment transport processes in the town.

There is a poor correlation between periods of high-intensity rainfall and recognised geomorphic changes brought about by flooding (Cave, 1987). Also, a detailed evaluation of significantly damaging river-related events in Arthur's Pass history is greatly limited by the lack of documentation post-1980. It is difficult to quantify the recurrence interval of widespread flooding with significant gaps in the literature. It is noted, however, that large-scale events such as the storms and subsequent floods similar to those seen in 1957 and 1979 are expected to have been reported in newspapers and journal articles. The lack of available articles between 1980 and 2006 suggests that there may not have been a storm or flood of a similar nature during this period, which accounts for the lack of specific details of fluvial hazards in the village.

A collection of the more serious flood events that have caused damage, injury or evacuation highlight the high frequency of these incidents (Table 6.3).

Date	***Details of incident***
1930	Heavy rains destroyed the bridge over the Bealey River on the Devils Punchbowl Falls track.
1932	Heavy rains eroded the Bealey River banks along the village area.
1938	Heavy rains caused the Bealey River to flood and erode along the riverbank adjacent to the village.
25-29 Feb. 1940	650mm of rain fell over less than 4 days at Arthur's Pass. Four families were evacuated from their homes.
1941	Heavy rains cause flooding throughout the township.
23-27 May 1950	775mm of rain causing severe damage to State Highway 73 and the railway near Arthur's Pass. Large sections were scoured out and approximately 90 000m^3 of shingle debris was deposited onto the road. The road was closed for several days for repair.
1950	The bridge crossing the Bealey River on the Devils Punchbowl Falls track is partially damaged.
26-27 Dec. 1957	Heavy rains caused flooding in the Bealey and Otira Valleys which closed the highway in Otira Gorge for several months. During the same storm, bridges and railway lines were heavily damaged, roads were washed out and undermined, whilst the railway embankments became major sediment sources. Bealey River partially aggraded.
Jan. 1964	Some flood damage was sustained in the township.
~1968 (exact date unknown)	Extensive flooding caused by heavy rains in the national park caused two houses to be destroyed in the village.
1975	Heavy rains cause flood which destroys bridge on Bridal Veil track.
2-3 Dec 1979	Heavy rains and subsequent floods washed away a temporary bridge at Rough Creek, and both McGrath Stream and the Bealey River aggraded.
14 Nov. 2006	Heavy rains cause Bealey River to swell and break the first stopbank along Crusher Loop. Houses protected by sandbags. A drainage culvert fails near Arthur's Pass General Store and floods the outdoor education centre.

Table 6. 3. Major fluvial-related events in recorded history that have caused damage to the Arthur's Pass village. (Beaven, 2006; Cowie, 1957; McSaveney, 1982b).

The Bealey River and other streams in the Arthur's Pass National Park have been a significant hazard to trampers in the past, especially those crossing tributaries unassisted. Numerous trampers and climbers have had to be rescued by emergency services, rescue aircraft or volunteer personnel on foot after being stuck by swollen rivers, particularly in heavy rain. 26 deaths by drowning have been recorded in the park since 1926 (Kates, 2008), several of which took place whilst attempting to cross a river in flood or during flash flooding in fluvial areas. Since 1998, 12 non-fatal flooding incidents have occurred in the national park (Kates, 2008).

Heavy rain and subsequent flooding have previously damaged sections of State Highway 73 on both sides of Arthur's Pass, cutting off transport in the area (Whitehouse & McSaveney, 1992). Much of the local infrastructure is vulnerable to washouts and water damage which has severely hindered emergency and welfare efforts in the past. Disruptions to the road are particularly evident in the Otira Gorge. Since the construction of the viaduct and rock shelter the risk has been minimised, but flooding and erosive processes are regularly functioning and will continue to be problematic in the future.

Sedimentation of the Bealey River was most evident after the December 1957 storms. Between 1960 and 1977, erosional processes removed much of the accumulated sediment as the river moved back into equilibrium and the small alluvial fans along the river were naturally revegetated, suggesting that they had become inactive shortly after the storm. Since then only minor aggradation has been observed in the river, most of it short-lived. Whitehouse and McSaveney (1992) propose that the Wardens Creek fan aggrades every three to four years and that the Rough Creek and Halpin Creek confluences are vulnerable to moderately frequent, large-scale aggradation.

The embankments surrounding the railway station and rail yard have the potential to become significant sediment sources. The section of rail immediately south of the tunnel is artificially raised and significantly modified. The volume of riverbed sediments on the southern side of the rail bridge near the Avalanche Creek confluence is variable because built up material is intermittently washed away by the Bealey River. The fluctuating volumes of sediment in this location are attributed to the narrowing of the river caused by the bridge abutments, which restrict the flow of water and riverbed materials until they have passed under the bridge and can move unobstructed along the remainder of the Bealey River.

Some areas of the village are low-lying and typically less than a couple of metres above the active river level. Previous hazard events signal where high-risk zones may be located in the future:

- most buildings on the east side of the highway, particularly properties on Crusher Loop and near the Devils Punchbowl Falls carpark. Buildings positioned on high ground or with specialty protective works installed, such as the railway station, are exempt from the high-risk zones.
- houses located on the Rough Creek fan, particularly the northern side where the stopbanks are not as efficient as other areas.
- properties along State Highway 73 that may be vulnerable to flooding from stormwater drain pipe blockages, such as the outdoor education centre and Mountain House backpackers.

6.7 OPPORTUNITIES FOR FLOODING, EROSION AND AGGRADATION TO THE RIVERBED IN THE FUTURE

Three realistic scenarios are suggested for the Arthur's Pass region that may initiate flooding within the village in the future:

1. Surface overflow of rivers and streams due to excess supply of water, lack of natural and man-made storage areas and reduced water transport capabilities due to sediment. This would cause temporary flooding to low-lying areas of the village, in the same way it has occurred previously, with impacts to both the physical and urban landscape. This also introduces potential water quality issues from road and rail traffic and sewage. However, due to the familiarity of the community to this type of hazard, they are well equipped to deal with recurrent floods of this nature. There is expected to be an increase in the severity and frequency of river-related events, which is attributed to changes brought about by global climate change.
2. Landslide damming both downstream and upstream of the village. The most vulnerable slopes identified coincide with the Graham Creek and Halpin Creek confluences with the Bealey River, downstream of the village. Upstream, numerous potential landslide dam sites have been identified between the village and the pass, originating from Mt. Cassidy, Rome Ridge and Goldney Ridge. The possibility and distribution of landslide dams in this area has been discussed in Chapter 5. The ramifications associated with landslide dam formation at Arthur's Pass are severe, albeit rare. The valley floor is steep yet highly constricted by the mountain slopes

on either side. Material obstructing the natural flow patterns of the river would – depending on the extent of the blockage – have catastrophic effects on the village.

3. Failure of the man-made drainage system in the urbanised area. Blockages and breakage of pipes and stormwater drains mostly aggravates an already present problem caused by excessive precipitation throughout the upper Waimakariri catchment. If drainage systems are impeded or not able to cope with the volume of water, potential flooding will occur. Surface runoff will also be exacerbated in the urban area as there is little opportunity for ground saturation.

Possibilities for erosion and channel incision in the future will be directed by:

1. An increase in annual precipitation due to global climate change, forcing a rise in the volume of surface runoff and intensifying the erosive capacity of the Bealey River catchment.
2. Confliction between the natural environment and urban sprawl encroaching on the floodplain, initiating channel avulsion and requiring the use of additional flood control measures.
3. Loss of vegetation through slope failure, continued erosion on the floodplain and clearing for developmental purposes. Vegetation acts to stabilise the river and its local environs and removal of vegetation would heighten the possibility for erosion in the future.

Possibilities of aggradation and sedimentation in the future are through:

1. Slope failures such as landslides, debris flows and minor slips that will contribute large volumes of sediments to the river.
2. The erosion of railway embankments, which may cause aggradation downstream because they have the potential to become significant sediment sources.
3. Channel avulsion that allows for sediment build-up in previously erosional zones.
4. Debris coming from the upper Punchbowl catchment may allow the Punchbowl Creek fan to build up to its original height (marked by an incised terrace). This would shift the river towards the highway and cause many problems for the village.

The small size of the town and the community involvement in assisting other residents allows emergencies to be responded to promptly and efficiently, using local resources. However, this could also be the town’s downfall, as only limited resources are available and the village relies heavily on outside organisations for assistance and response equipment when required. Because river-hazards are very localised, the implications of the town's isolation are not as acute as they would be in the case of a widespread earthquake. The main concern would be access issues during peak flood periods.

Further expansion of the town is anticipated to be low because of the low number of freehold sections available in the village and because of restrictions imposed by the National Park Management Plan 2006, which aims to maintain the integrity of the natural environment. Nevertheless, several yet to be approved proposals are currently under consideration that could elevate the risk. These include several realignment projects, focusing on the Rough Creek road bridge, the Rough Creek to Snow Creek section, the village to McGrath Stream section and along minor encroachments throughout the vicinity of the settlement. Landscape improvement has been recommended for the Arthur's Pass railway yards, the village river protection works and at the Devils Punchbowl Falls carpark area to the north of the village. It is not known whether any additional buildings within the settlement are anticipated or whether any proposals would gain building approval due to the vulnerability of the village and the lack of suitable land for development.

The redevelopment of the public toilets, bus parking and rest stop opposite the DOC Visitor Centre was completed in late-2007. It has resulted in the repositioning of sewage works closer to the Bealey River, which may create unforseen issues regarding sewage treatment, disposal and contamination of the river system. Other sewage treatment areas, particularly those servicing the Sunshine Terrace area, have had recent maintenance work carried out to ensure they are safe and unlikely to contaminate the local environment. It is thought that the safest place from flooding would be at the train station and rail yard. This area is on higher ground than other areas directly next to the river and it is protected on almost all sides by stopbanks and large embankments built to safeguard the railway line into the tunnel.

6.8 PREVENTATIVE TREATMENT METHODS FOR RIVER-HAZARDS

Control and protection measures used in flood-prone areas around the world are not necessarily applicable to Arthur's Pass, because river problems in the village have arisen out of poor placement of human activities in a region where natural processes such floods and channel avulsion would normally continue uninterrupted. Smith (2004) describes six methods of flood-proofing vulnerable regions. When applied to the Arthur's Pass field area, only three are realistically possible:

- DRY FLOOD PROOFING – Sealing the property so flood waters cannot penetrate the building.
- RELOCATION – Moving the building to higher, less-vulnerable ground.
- DEMOLITION – Removing a building in a flood-prone area and either rebuilding a flood-proof building in the same site or rebuilding in safer area.
- FLOODWALLS – Building a flood-proof wall around the building to protect it from river overflow.
- ELEVATION – Placing a building above the river flood level on stilts so it is protected from incoming water.
- WET FLOOD PROOFING – Making ground level sections of the building resistant to flood damage and allowing water to enter during floods.

Dry flood proofing, relocation and demolition are the most realistic and attainable flood-proofing measures at Arthur's Pass, although there are limitations to each of these because of building codes, land-use regulations and provisions set out in the Resource Management Act 1991, Building Act 2004, Selwyn District Plan and Canterbury Regional Plan. Also, they may apply more to slow-moving type floodwaters and less to the fast-moving types present in the Arthur's Pass region.

It is difficult to assess whether implementation of flood protection measures such as these are cost-effective enough to be put into practice on Arthur's Pass properties. Periodic damage to houses is very localised and often minimal. Relocation and demolition are extreme reactions to a problem that may not be severe enough to warrant such actions. However, developers of any future buildings should consider incorporating more long-term measures such as dry flood proofing and elevation to assist in reducing the flood hazard. Appropriate land-use planning and preparedness are also key factors in lowering the risk of river-hazards in the community.

Severe events similar in nature to the 1957 and 1979 storms are expected to have a return interval of between 25 and 100 years. Because the Building Act 2004 requires structures to have a design life of at least 50 years, it would be necessary to plan and mitigate for events of comparable magnitude and severity that may take place in future.

Home evacuation has taken place rarely in the past and is typically a used as a final measure when all preventative remedies have been exhausted. Many of the houses at Arthur’s Pass are holiday homes and have only transient guests, so many remain uninhabited for long periods of time, further reducing the probability of building evacuations being required. Stopbanks are considered to be the most satisfactory means of controlling the river because they can be manufactured out of locally sourced river gravel and are comparatively low-cost. The use of several generations of stopbanks over the last 90 years have proven adequate protection in the vast majority of river-related events, especially when used in conjunction with other methods of defence such as sandbags.

6.9 CURRENT METHODS OF RIVER CONTROL AT ARTHUR’S PASS

Extensive river protection methods are aimed at safeguarding the village and its adjoining land, and infrastructure such as power transmission lines, the state highway and the railway track through the valley. The Arthur’s Pass National Park Management Plan 2006 outlines the use of natural gravel stores to form these protection works where possible in order to retain the integrity of the natural environment. It is also noted that removal of gravel from the riverbed is permissible because it has a low environmental impact as there are large volumes of gravel available in the Bealey Valley where the material is regularly replenished by natural fluvial processes.

The most featured engineering method of river control at Arthur’s Pass village is ‘rip-rap’ stopbanks. The term ‘rip-rap’ simply means large boulders that are accumulated along areas in need of protection. At Arthur’s Pass, ‘rip-rap’ stopbanks are evident for long stretches along the Bealey River in front of the village (Figure 6.5). In several cases, there are two or three sets of stopbanks, functioning as a backup system if the first stopbank fails. Examples of this are observed near buildings on Crusher Loop and on the northern side of Rough Creek beside dwellings situated on the Rough Creek alluvial fan. The stopbanks commence at the top of the Devils Punchbowl carpark area and continue intermittently before ceasing at the Graham Stream river mouth south of the village.

Gabions are a supplementary means of stopbank river control and only appear at Arthur’s Pass in small groups, many of which have been partially buried over time (Figure 6.6).

Figure 6. 5. A double line of 'rip-rap' stopbanks formed from natural riverbed gravel (left and centre) along the Bealey River (right) in front of Crusher Loop.

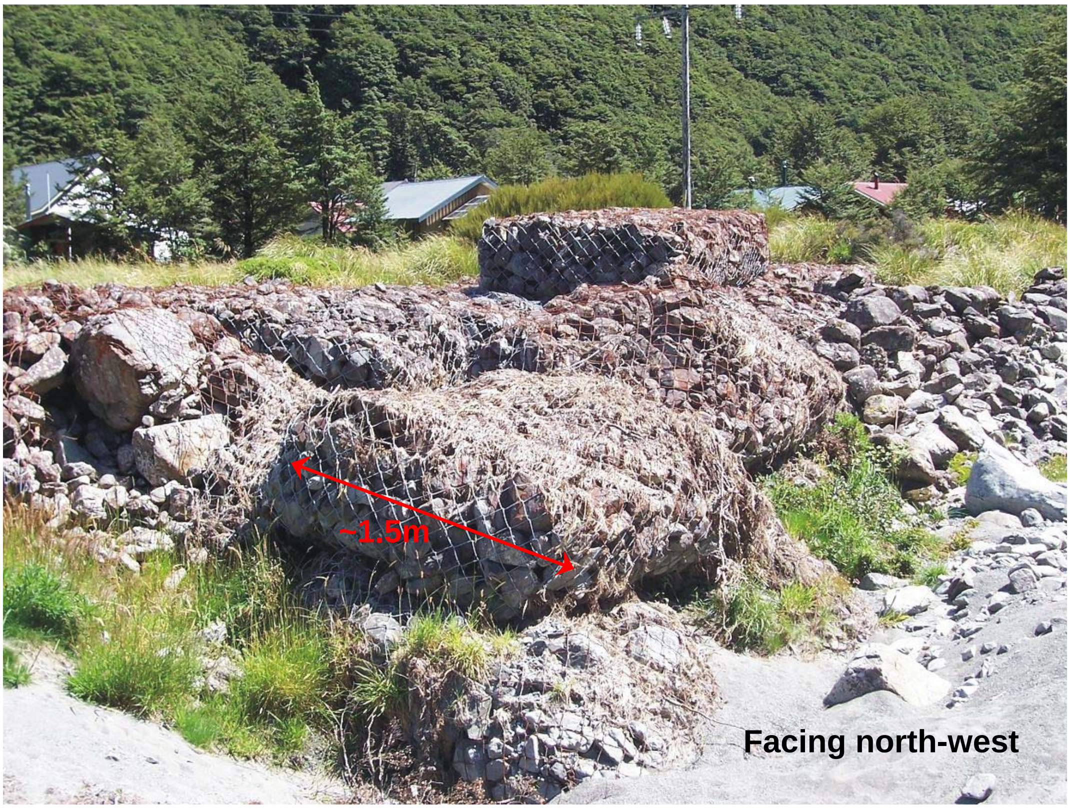

Figure 6. 6. Partially buried gabion stopbanks on the Bealey River bank opposite the Otira Tunnel entrance.

The placement of gabions within the village is typically perpendicular to the ‘rip-rap’ stopbanks, most likely to assist in the redirection of flood waters away from the ‘rip-rap’/permanent stopbanks, much like a groyne diverts water at the beach and alleviates sand build-up in certain areas. The ‘rip-rap’ stopbanks, particularly the more established ones, are less permeable than the gabions and provide a marginally better defence against rising river levels than the gabions, which is possibly why they have been favoured.

Similarly, the Midland Railway Company constructed site specific embankments to shield the rail network, railyards and station from flood waters. The highest of these embankments runs underneath the railway line between the Arthur’s Pass railway station and the Otira Tunnel. Between the Bealey River and the station there is a 5-6m drop (i.e. the station has been placed on high ground). Approximately every 10m, gabions measuring up to 5m in length align perpendicularly from the bank. Nine were counted in total in this area. Gabions also constitute part of the stopbanks on both sides of Rough Creek. There are generally only two or three stacks high and extend up to 5m in length. Both Transit NZ and New Zealand Railways Corporation are responsible for many power transmission lines and river protection works around the railway track and rail yard. The Arthur’s Pass Association and Selwyn District Council also contribute to stopbank funding and maintenance (Beaven, 2006).

On the opposite bank to the tunnel entrance there is a line of concrete block retaining structures in the form of $1m^3$ concrete blocks with large steel rods protruding from each side (Figure 6.7). However, they are positioned at such an angle and in such a location so as to offer little protection and therefore would not contribute greatly to flood control along the Bealey River.

Depending on the severity and duration of the rain, the flooding may breach stopbanks and reach houses on the riverbank. During isolated incidents, sandbagging is a common practice among the town residents and is used as a method of controlling the river water by blocking and diverting incoming flood waters if they breach the stopbanks along the Bealey River and Rough Creek. Even moderate increased water flow in the Bealey River is enough to significantly increase the river levels and aggravate erosion along the riverbed. Along Crusher Loop, the developed land lies only metres above the active river level. It is difficult to assess the ability of Rough Creek stopbanks to protect from debris flows, as the highest point of the stopbanks is only 2-5m above the riverbed (Figure 6.8).

Figure 6. 7. Concrete retaining structures near the Avalanche Creek and Bealey River confluence protecting the railway embankment (to the left out of picture).

Figure 6. 8. A 'rip rap' stopbank along the lower south bank of Rough Creek protecting the police station and several houses on Sunshine Terrace.

There are some doubts as to the protective capabilities of the outer stopbanks in Rough Creek and along the Crusher Loop section, particularly because many appear to be old and not adequately maintained. Past experience, however, demonstrates that the inner stopbanks may act to reduce the volume of incoming water enough to allow for alternate, temporary reinforcements, such as sandbagging, to be installed.

Observations taken of the river level progressively throughout the year indicate that the flow of water is seldom more than an easily-crossable stream along the riverbed formed of large boulders. Conversely, the size of the Rough Creek deposits is representative of the debris that the creek is capable of transporting. Some of the houses on the fan, particularly along Sunshine Terrace, have remained undamaged since the formation of the town. No confirmed debris flows or damaging floods have been recorded along Rough Creek in documented Arthur's Pass history.

From a social perspective, the Department of Conservation and most customer services in the town release daily cautionary information to visitors, advising of the river conditions in the national park. This is currently the only form of pre-emptive information available with up-to-date river conditions and currently serves its purpose well.

6.10 SUMMARY

The fluvial system within the Bealey Valley is very dynamic and somewhat unpredictable. The numerous river hazard events that have taken place in the past suggest that river-related issues are ongoing and continuous, and therefore must be mitigated at Arthur's Pass. The results of this fluvial-related hazard assessment demonstrate that:

1. The Bealey Valley is formed by fluvial channels and is highly vulnerable to river flooding, erosion, aggradation and channel avulsion. Factors that make the Bealey Valley susceptible to these fluvial processes include the large size of the catchment, the wet and windy climatic conditions in the region, the lack of adequate water storage both natural and man made and the encroachment on the floodplain by human activities.
2. Many geomorphic changes have been recorded in the river system in the Bealey Valley, most of which give an indication of what is to be expected in the future. The Bealey River is the largest tributary in the valley and it is on the Bealey River

floodplain that the village is located. The river is constantly being naturally modified but it is particularly sensitive to human impacts brought about by urban development and the installation of roads and bridges.

3. Perceptible changes in contributing tributaries in the Bealey Valley show that numerous cycles of erosion and aggradation have taken place within the valley. A number of previously active zones have become stabilised and revegetated, and other previously stable zones within the floodplain area have become remobilised over time.
4. The documentation of past fluvial-related events impacting the village is limited, but several major events have been recorded. These include the December 1957 storm, the May 1950 storm, the Dec 1979 storm and the November 2006 storm, most of which resulted in extensive flooding in the village, minor slips closing the road and damage to bridges and buildings. 26 people have drowned in the Arthur's Pass region since 1926, several of which were during heavy rain periods, and 12 non-fatal injuries have been attributed to floods in the last decade.
5. Future issues associated with the river system in the Bealey Valley will continue to be surface flooding within the village and erosion and aggradation of the riverbed. More serious potential hazards have been recognised in the form of landslide dams, which would be catastrophic to the village, the avulsion of the active channel towards the developed village area and failure of man-made drainage systems so they are not able to cope with high volumes of surface runoff.
6. Preventative treatments for river-related hazards at Arthur's Pass range from less invasive methods such as dry flood proofing buildings to drastic measures such as relocation and demolition of affected buildings. The cost effectiveness of such measures may not make them ideal for the Arthur's Pass environment.
7. Current methods of river control at Arthur's Pass include extensive stopbanks, gabions and occasional sandbagging. There is possibly a lack of adequate physical barriers which suggests that there is potential for river-related hazards to be managed better in the future.

CHAPTER 7
HAZARD ANALYSIS AND MAPPING

7.1 INTRODUCTION

This chapter aims to investigate the natural hazards at Arthur's Pass on a broad scale and introduces the use of hazard maps to assist in hazard management. An understanding of the behaviour of hazard processes is a fundamental requirement of any hazard analysis. If the hazard is not understood it is not possible to make realistic assessments of community vulnerability, which increases the chance of an unreliable estimate of the natural hazard risk being made (Nott, 2006).

The specific objectives of the hazard analysis chapter are:

1. To explain aspects of vulnerability and assess the areas at Arthur's Pass most vulnerable to social, structural and infrastructural impacts from natural hazards.
2. To discuss the interrelationships between seismic hazards, meteorological hazards, mass movement hazards and fluvial-related hazards at Arthur's Pass and how they influence each other.
3. To outline the methods used in the construction of three hazard maps of Arthur's Pass and justify the designation of hazardous zones within these maps.
4. To discuss probability estimates for all the natural hazards at Arthur's Pass and explain the limitations associated with these estimates.

7.2 RESEARCH LIMITATIONS

Natural hazard analysis is often based around the notion that the behaviour of natural systems and the incidence of past hazard events can be used to forecast events likely to take place in the next 50 to 500 years (Grant, 1998). Several centuries of data is required for a long-term hazard assessment to be reliable and to constrain recurrence intervals of most hazard events (Cowan, McClure, & Wilson, 2002). Acquiring estimates of hazard occurrence with any statistical precision is impossible in the Arthur's Pass region because of the lack of long-term historical hazard data, which makes the use of this method alone unsuitable (Nott, 2006). Current records of seismic and landslide data are only appropriate for capturing the short-term or immediate risk. As the local hazard record for the village only extends back 100 years at best and the national hazard record 150 years, there is insufficient data available to reliably and confidently estimate probabilities.

Undertaking a hazard assessment of the Arthur's Pass landscape and producing a series of hazard maps which can be used by local agencies is a difficult task. Producing such hazard zonations has severe limitations because of the extremely volatile and changeable nature of the geomorphic, tectonic and atmospheric processes that exist in the area (Grant, 1998).

There are also major limitations to this research in terms of the determination of exact probability estimates and expected magnitude and severity of events. In certain cases there is even difficulty ascertaining definite locations that are vulnerable to hazard processes. This problem could be partially alleviated with the implementation of geological and geotechnical data from in depth investigations. Such an investigation goes beyond the scope of this study but would form a basis for future research.

7.3 VULNERABILITY

The vulnerability of a community is a fundamental consideration when assessing risk factors and preparing hazard zonation maps in a village such as Arthur's Pass. Specific weak points in the management of emergency situations need to be addressed so that the town and its residents can be better prepared for a natural hazard event. Several social and infrastructural vulnerabilities exist at Arthur's Pass. They are outlined below.

7.3.1 Aspects of vulnerability

Vulnerability is initially generated by economic, political and social processes. The degree of vulnerability and loss also depends on the population distribution and the environmental conditions in the region, natural or otherwise (Bell, 1999). The more resilient a community is to natural hazards, the lower its vulnerability. In comparison to other global regions, New Zealand has a stable government, a profitable economy and well-developed social systems, and Arthur's Pass specifically has a moderate to low population density. This would lead to the assumption that Arthur's Pass has a low vulnerability. However, the attribute that makes Arthur's Pass exceedingly vulnerable to natural disasters is the highly dynamic geomorphic environment within the Southern Alps, which the village is a part of.

Currently the most prominent flaw in the hazard mitigation of the township that perhaps contributes to its vulnerability is the lack of total self-sufficiency. The village is not equipped to deal immediately with major medical emergencies, aerial searches and rescue, transporting large numbers of people or earthmoving; all services that may be required after a natural disaster in the area. Obviously the town is not large enough to cost-effectively support these kinds of permanent services onsite. However, following a large magnitude regional event, the village is likely to be cut off indefinitely from other South Island regions and be without life-saving resources for extended periods. Other vulnerable aspects of the Arthur's Pass village relate to people, property and infrastructure, all of which may serve to increase the loss due to a natural disaster.

7.3.1.1 Social vulnerability

The safety of people within the national park and village is the highest priority in this hazard analysis. Several factors contribute to the social vulnerability of the village:

- Most people in the village are non-residents who have little prior knowledge or experience of the hazards within and immediately surrounding the town. There may also be issues created from the language barrier with tourists in the town, which would make a coordinated evacuation more difficult.
- Individuals within the village and in other areas of the national park are more vulnerable to small-scale hazards such as rockfalls and flooding, but the community as a whole is also vulnerable to rare catastrophic disasters such as landslide damming and high magnitude earthquakes that will cause widespread and numerous casualties, primarily because of the lack of nearby rescue equipment and welfare items.
- The town is very isolated and confined to the Bealey Valley with only one major thoroughfare. If the main transport routes become blocked, people will effectively become trapped.

7.3.1.2 Property vulnerability

All new buildings and renovations to previously existing structures at Arthur's Pass must conform to regulations set out in both the Building Act 2004 and Resource Management Act 1991. Furthermore, it is mandatory for local and territorial agencies to monitor and record natural hazards in the village and disclose this information to interested parties, as well as restrict or prohibit developments in regions deemed unacceptably hazardous (Grant, 1998). Vulnerabilities to structures exist in the form of:

- The 142 buildings within the village boundaries that are categorised as ‘habitable’; all are included in emergency procedures. They comprise mostly flexible wood and aluminium frames but a few buildings are built using rigid masonry, which is prone to crumbling during earthquakes. Many of the buildings have brick chimneys which have historically been one of the major structures damaged during earthquakes.
- Houses in the township that are at risk of being lost or damaged in flood events, from fires caused by lightning strikes, as a result of seismic shaking and from strong wind gusts (Beaven, 2006).

7.3.1.3 Infrastructural vulnerability

Elements of infrastructure and buildings within the town are most likely considered to be affected even by small-scale events. Arthur’s Pass town infrastructure consists of:

- Roads, particularly the State Highway 73 corridor between Halpin Creek and the Otira Gorge, but also smaller dirt tracks and access roads around the village.
- The railway track, Otira rail tunnel and the Arthur’s Pass Station and rail yard. Both cargo trains and passenger trains pass through the village several times every day.
- Communication links, including the landline digital exchange connected by underground fibre optics to the parent exchange in Darfield, the television broadcast repeater on the flanks of Mt. Rolleston and the Vodafone and Telecom mobile phone towers located adjacent to the rail yard (SoftRock NZ, 2008a).
- Electricity towers and power poles stretching along the length of the village and the Arthur’s Pass Power Substation in the southern region of the village.
- Sewage pipes on sections south of Rough Creek, which are connected to a small waste treatment plant at the southern end of Sunshine Terrace. It is assumed that areas north of Rough Creek have individual septic tanks and treatment systems because no treatment plant exists north of Rough Creek.
- The water supply, which is gravity fed from Avalanche Creek.

Landslides and rockfalls generated by seismic shaking present a serious threat to both underground and overhead infrastructure within the town. Such severe damage to services has the potential to seriously alter the success of the recovery phase following a natural disaster (Environment Canterbury, 1990).

7.4 HAZARD ZONATION

Hazard zonation and land-use planning are methods of adapting to natural hazards. They are also key factors in the development of community resilience. The integration of effective land use planning and hazard mitigation is a necessary step towards reducing the risk to the Arthur's Pass community (Burby, 1998). The multi-hazard concept describes the interrelationships between the various natural hazards at Arthur's Pass so that hazard behaviour can be better understood and integrated into hazard management programs (Figure 7.1).

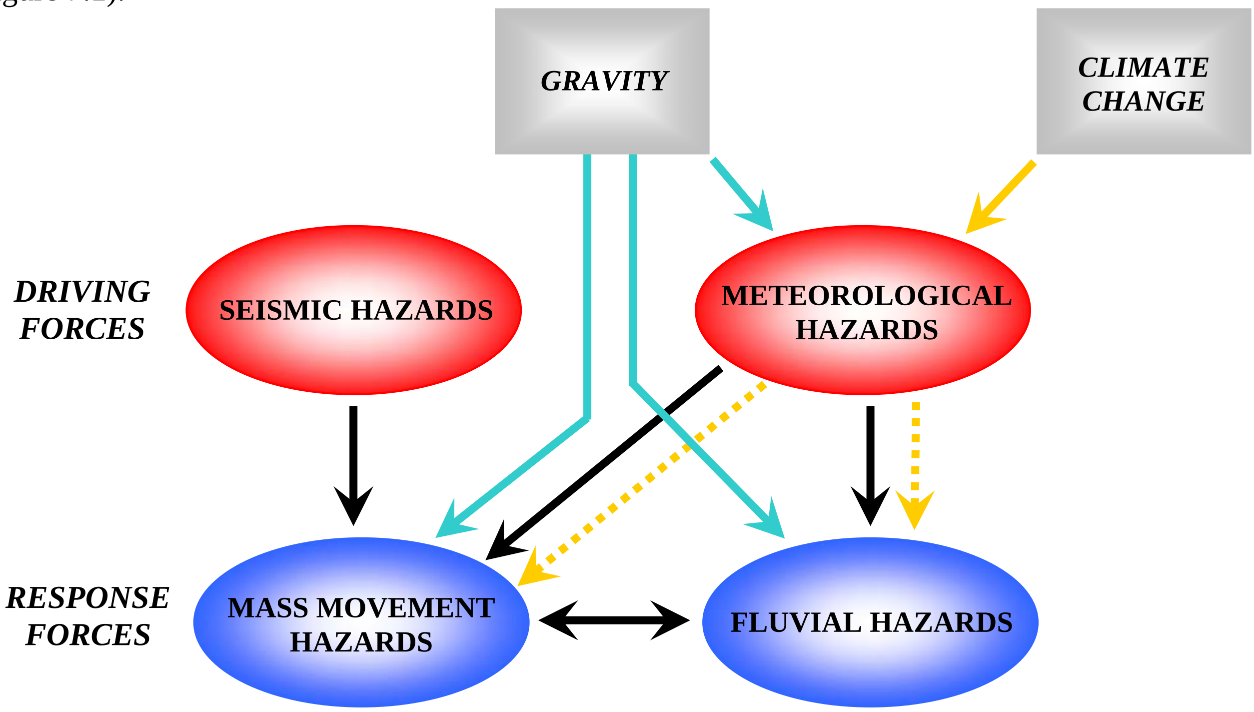

Figure 7. 1. The interrelationships between the identified hazards at Arthur's Pass between "driving" forces (seismic and meteorological hazards) and "response" forces (mass movement and fluvial-related hazards). The changes brought about by climate change and gravity also influence meteorological, mass movement and fluvial hazards.

7.4.1 The multi-hazard concept

Hazards occur randomly and show a high variability in time scale, intensity and magnitude. It is acknowledged that seismic and atmospheric hazards have distal sources and are linked to external processes that originate away from the hazard affected area. Fluvial and mass movement hazards are sourced proximally and are internally structured, so that the hazards tend to initiate in the same area that they affect. Both mass movements and fluvial hazards are easily modified by external forces. They are the "response" hazards. Seismic and atmospheric hazards are the "driving" hazards and produce the forces required to trigger mass movement and fluvial responses.

SEISMIC HAZARDS are wholly independent; they are not affected, influenced or controlled by human activities or other hazard mechanisms. Their prediction is extremely difficult and can not be estimated with any degree of certainty, especially in the short-term. Furthermore, seismic hazards can be described in general terms as having a one-way dependency (they trigger other hazard events but they themselves are not caused by other hazards) (Seville, 2006).

METEOROLOGICAL HAZARDS are independent from other hazards (except perhaps volcanic hazards) but they can be affected by long-term human factors, such as global warming. They are highly seasonal and can be predicted days in advance. They also have a one-way dependency.

MASS MOVEMENT HAZARDS have a number of both natural and man-made causative factors and they can to some extent be influenced, controlled and prevented by human activities. They are known to occur in specific conditions, such as during storms or after a seismic event. Unstable slope locations can be pinpointed, but the exact timing of occurrence of mass movements, particularly large-scale events, cannot be predicted with great accuracy. Mass movements produce both one-way and two-way dependencies (when the occurrence of one hazard affects the occurrence of the other and vice versa). An example of a one-way dependency is that landslides are caused by rainfall, but rainfall levels are not affected by landslide occurrence. As a two-way dependency, mass movements can alter river processes and contribute to fluvial hazards. Conversely, fluvial hazards play a role in the initiation and distribution of mass movement events (Seville, 2006).

FLUVIAL-RELATED HAZARDS and flooding occur over varying time scales and are highly dependent on the occurrence of meteorological and mass movement hazards. They can be modified, controlled and prevented to some degree, and they can usually be forecast in the short-term. In much the same way as mass movement hazards, they consist of both one-way and two-way dependencies with other hazard types. In both mass movements and fluvial hazards, a reinforcing feedback loop is created, in which the occurrence of one increases the occurrence of the other (Keey, 2000).

It is possible to establish that in many cases the identification of specific hazards is likely to be a precursory signal for other hazard types. For example, the spatial and temporal distribution of landslides is related to the distribution of fault lines and the distribution, duration and intensity of meteorological events. Using this logic, it is clear that simultaneous hazard occurrence is extremely common throughout the Arthur's Pass region.

Multi-hazard scenarios that are regarded as significant to the Arthur's Pass area are numerous and involve complex relationships. For example:

- According to Environment Canterbury (1990), extensive storm-induced mass movement events take place in Southern Alps catchments at least once in a 100 year period. Such widespread mass movements are also expected to be associated with flood scour and debris depositional processes in regions such as Arthur's Pass.

- Landsliding and flooding are closely allied at Arthur's Pass because they both are related to precipitation, ground saturation and runoff (Jochim & Colorado Geological Survey, 1988). They often occur simultaneously under similar atmospheric conditions and both affect the prevalence of fluvial hazards, particularly along the Bealey River adjacent to the township.
- Debris flows occur in narrow gullies throughout the Southern Alps and are often mistaken for floods. Rough Creek and McGrath Stream are more likely to accommodate debris floods, which represent the midpoint between debris flows and regular floods (Welsh, 2007). However, there is definite evidence of debris flows on the fan, indicating that both processes may occur in the area.
- High-magnitude rupture of faults within 10km of Arthur's Pass may potentially trigger landsliding on more than 60% of slopes in the area, having a major impact on transport routes and the function of town services (E. Smith, 2004).
- Existing earthquake data suggest that earthquake intensities of more than MM 9 would be required to initiate a rock avalanche in the Arthur's Pass area, and that ground shaking intensities above approximately MM 6 would be enough to initiate slope failures around Arthur's Pass that would cause considerable damage to the highway (Paterson, 1996).
- Storm events are responsible in part for the intermittent aggradation of Wardens Creek, Halpin Creek and Rough Creek. Wardens Creek is expected to aggrade every three to four years. Rough Creek and Halpin Creek tend to experience aggradation on a more frequent basis (Whitehouse & McSaveney, 1992).

7.4.2 Hazard maps

The most accessible means of conveying the degree of risk for specific hazards is through hazard mapping. Ideally, all hazards should be represented on the same map, although this is not always possible. Complications arise when multiple hazards are evident in a risk zone, more so when the occurrence of one hazard is linked to the occurrence of another, as is the situation at Arthur's Pass.

Most of the hazards that exist at Arthur's Pass are rapid-onset events that contribute only a minute percentage of the overall hazard risk throughout New Zealand (Wisner et al., 2004). Despite this, site-specific maps showing the status of hazards at Arthur's Pass are vital because of the comparatively dense distribution of hazards in such a small yet populous area. The locational approach to hazard mitigation aims to reduce life and property losses from future disasters by placing limits on the urban development and usage of hazardous areas (Burby, 1998). This notion has been employed as a major objective in the construction of hazard maps showing hazard vulnerabilities at Arthur's Pass.

Additionally, the Building Act 2004 stipulates that the design life of structures is at least 50 years, to ensure the safety and durability of buildings in the long-term. Consequently, taking into account this minimum design life of structures was deemed important to illustrate the hazards both in the short- and long-term, so that natural hazards can be integrated into spatial planning practices and emergency preparation.

The application of hazard mapping as a tool for risk reduction has previously been described and employed by numerous authors. Chamberlain (1996), Grant (1998), Inwood (1997), Paterson (1996), Smith (2004), Smith (1990), Speight (1933), Whitehouse and McSaveney (1992) and Yetton (2000) all give examples of hazard maps within New Zealand.

7.4.3 Methodology

Any spatial aspect of a hazard can be mapped over a variety of time scales provided that there is enough information available on its distribution (Bell, 1999). However, rating hazards on a scale of expected severity is not possible without the input of previous events.

A chief objective when producing the hazard zonation map and designating areas which were deemed more at risk than others was to have it in a form that is comprehensible to both scientists and lay persons. Most often these maps are used by local government agencies because they provide an important tool for implementing preventative measures and as such need to be easily readable and understood (Ni, Liu, Wai, Borthwick, & Ge, 2006).

It became obvious early on in the mapping stage that a single map at a certain scale would not suffice for the representation of many different hazards occurring over highly variable temporal and spatial scales. In previous hazard research projects, authors have used a variety of mapping techniques to convey as much information as possible by customising the map to fit all hazard parameters. Assessment of such mapping methods to check for their suitability to this project did not yield any appropriate techniques and as a result, a completely different approach has been taken.

It was decided that three separate map sheets would illustrate the Arthur's Pass hazard conditions most effectively. Each map sheet contains a regional map (covering approximately 250km^2) and a local map (showing just the Arthur's Pass village area – approximately 4km^2). This format was selected to ensure that all hazards were accommodated at different spatial distributions. The map sheets cover three different probabilities of occurrence; >2%, 0.2-2% and <0.2% annual exceedence probability (0-50 year, 50-500 year and 500+ year time intervals respectively). The time intervals are large enough to show considerable geomorphic changes as a result of dynamic natural hazard processes and also fit into Building Act 2004 regulations whilst maintaining enough detail on the timing of events to be useful to hazard managers.

The construction of the hazard maps is restricted by wide-ranging limitations including:

- the chaotic and long-term unpredictability of the drainage network within the Bealey Valley,
- the unknown effects of seismic events on sediment contributions to the river,
- the lack of flood and landslide magnitude and frequency data for Arthur's Pass,
- the as yet unknown effects of climate change on atmospheric conditions and patterns, and
- the absence of a complete historical record of all natural hazard events in the Arthur's Pass region.

7.4.3.1 Mapping seismic hazards

Both major and minor fault lines were investigated and collectively placed onto one large regional map. Due to difficulties in determining specific return periods for most faults affecting the Arthur's Pass region, all apparent faults are shown on each of the three map sheets. In addition, no distinction has been made between definite, approximate and inferred fault boundaries because of the high uncertainty associated with many of these faults, but they have been divided into major and minor faults as outlined in Chapter 3.

7.4.3.2 Mapping meteorological hazards

Apart from avalanches, no meteorological hazards have been shown on the maps because their occurrence is very uniform over a widespread area, with very little variation over much of the Arthur's Pass National Park. Events that are presumed to behave like this include rainfall, snowfall, strong winds and climate change, all which take place evenly over a limited areal extent that includes the Arthur's Pass township. The mapping of avalanches mainly took advantage of maps and descriptions of past avalanches and projected avalanche zones provided by Arthur's Pass Mountaineering (2007). It is extremely difficult to predict the behaviour and distribution of avalanches in the future because of global warming and gradual geomorphic changes. Hence, the same avalanche zones have been illustrated on all three regional maps. Any increase or decrease in the frequency of avalanches is expected to be more or less solely associated with changes in annual snowfall and prolonged variations in snow levels brought about by processes such as climate change and El Nino.

7.4.3.3 Mapping mass movement hazards

Mass movement hazards were separated into debris flows/debris floods and all remaining mass movements (landslides, rockfalls, topples, rock avalanches and minor slips). For both the >2% (0-50 years) and 0.2-2% (50-500 years) annual exceedence probability maps, mass movement distribution closely follows the distribution of previous slope failures as observed on aerial photographs over 80 years and satellite images from Google Earth. Identification of mass movement zones on the map sheets has been based on the theory that natural hazards tend to occur in areas that have previously sustained slope failure, and subsequently very few new zones of weakness for these intervals have been identified. Larger, more catastrophic slope failures fall into the <0.2% annual exceedence interval (500+ years) and projected failure zones have been outlined on the corresponding map.

The mass movements for the <0.2% annual exceedence probability map are fundamentally considered to signify catastrophic events resulting in a partial or total destruction of the village area, either instantaneously or progressively. These mass movement zones have been inferred using evidence of previous major changes to the landscape and indications of possible future slumping on the slopes surrounding Arthur's Pass village. Mass movement mapping at an extended time scale such as this is an estimate at best, because evidence of previous large-scale events are largely overprinted or absent and do not allow for conclusive assumptions to be made on future catastrophic mass movements.

Debris flows have been omitted from the >2% (0-50 year) map because active flows have not been recorded in the village in the last 50 years. However, it is still possible for a debris flow to occur in the immediate future.

7.4.3.4 Mapping fluvial-related hazards

There were several components in the mapping of fluvial-related hazards that vary quite drastically over the three time intervals because of the highly active and changeable nature of river processes at Arthur’s Pass. Floods for the >2% (0-50 years) and 0.2-2% (50-500 years) intervals were roughly positioned within the current floodplain boundaries. Extra data on previous flood occurrence were also used to refine the position of possible flood levels for these time intervals. A flood with a recurrence interval over 500+ years is expected to be a catastrophic event at Arthur’s Pass. Flood levels in such cases may submerge the village with up to approximately 50m of water and sediment, so the predicted flood level for this interval was projected to be along the 800m elevation contour. One notable point is that despite the river levels differing quite severely over the three mapping intervals, the flooded area remains narrowly confined for all three on account of the steep slopes bordering the Bealey River.

Aggradation and erosion were monitored over the last 80 years using aerial photographs and Google Earth satellite images, and are backed up by field reconnaissance. Evidence of these fluvial events and some mass movements may have been modified or removed by subsequent fluvial processes but in many cases it is possible to identify alluvial fans built up over several decades or several centuries, so the occurrence of fluvial process can be predicted with a reasonable degree of accuracy.

The mapping of channel avulsion over the three time intervals also chiefly used aerial photos, satellite images and field investigations. It also took into account floodplain elevations, the bedrock geology, alluvial sediments and moraine deposits within the valley and the path previous river channels have taken. Once again it is difficult to determine with absolute certainty the paths that the active channel will adopt in the long-term, so mapped channel boundaries are best estimates of future channel routes.

7.5 ESTIMATED LIKELIHOOD OF HAZARD OCCURRENCE

Traditionally, natural hazards have been quantified using statistical methods. If it is possible to obtain probability estimates of a specific hazard, the estimate can be compared to the likely consequences of the event in order for appropriate action can be taken to mitigate the hazard (Yetton, 2000). However, in most cases, the natural hazards at Arthur's Pass do not yield sufficient information for confident estimates of their timing and severity to be made. Previously, qualitative risk assessments have not been attempted for every type of natural hazard. This may in part be due to the high number of uncertainties that are attached to hazard estimates even when the risk can be quantified (K. Smith, 2004). However, several probability models have been developed for natural hazard analysis that attempt to determine the time between events and recurrence intervals.

Under ideal conditions, the magnitude-frequency relationship of natural hazard events demonstrates that magnitude is inversely related to frequency. In practice, however, the highly dynamic nature of the environment is liable to generate unexpected events that may deem many hazard assessments using this method inadequate. Furthermore, this probability model is best applied only to large numbers of distinct, frequent, yet randomly occurring hazards (such as flooding, selected types of slope failure and some meteorological events) that fit into the Poisson probability model (Grant, 1998). This method is not particularly suited for determining details on seismic hazard occurrence because it assumes that earthquakes are independent events, and hence ignores elapsed time since the last tremor along a specific fault line (Yetton, 2000).

Landslide hazard maps tend to illustrate the physical attributes of potentially damaging mass movement events in terms of estimated volume, frequency and failure mechanism (Neaupane & Piantanakulchai, 2006). Physical calculation of quantitative values for these parameters is highly challenging at Arthur's Pass given the lack of conclusive and reliable data. Determining such values is considered outside the scope of this study but it is noted that there is a constant background risk of these hazards taking place at any time.

Disaster patterns can become evident over short time periods, such as 50 years, but for any realistic, long-term frequency-magnitude estimates, detailed records dating back several centuries are essential. On account of the lack of such data pertaining to the Arthur's Pass area, it is impossible to make any precise calculations for the likelihood of natural hazards.

7.6 SUMMARY

All natural hazards present at Arthur’s Pass are interconnected and have variable effects on other natural hazard processes. By analysing the characteristics of historical events and the relationships that exist between hazard processes it is possible to better understand hazard behaviour. This can then be used to construct hazard zonation maps which assist in hazard management and planning for the future at Arthur’s Pass. The results of this hazard analysis and mapping section demonstrate that:

1. Arthur’s Pass is highly vulnerable to natural hazards because of social, structural and infrastructural elements that may be susceptible to serious damage during a natural disaster. The high vulnerability and lack of total self-sufficiency of the village may impact on the success and timing of recovery efforts after a disaster event.
2. The multi-hazard concept is used to describe the complex interactions and relationships that exist between different natural hazards at Arthur’s Pass, because all hazard processes have an effect on other hazards. Gravity, seismic and meteorological hazards are “driving forces” and cannot be controlled or caused by human activities. Mass movement and fluvial hazards are “response” forces and are partially caused by the “driving” forces and human activities.
3. Hazard zonation is a method of adapting to natural hazards and the most effective means of displaying hazard information is in the form of hazard maps. Three hazard map sheets have been constructed for the Arthur’s Pass area, showing both regional and local scale hazards for >2%, 0.2-2% and <0.2 % annual exceedence probabilities (0-50, 50-500 and 500+ year average return periods). Several factors restrict the accuracy of hazard map development, including the unpredictability of environmental and geomorphic processes, the unknown effect of climate change and global warming on natural hazard conditions and the lack of historical data on previous landscape behaviour.
4. A long record of previous event data is required to make accurate probability estimate for the occurrence of natural hazards at Arthur’s Pass, hence the comparatively short historical record does not allow for reasonable probability estimates to be made. Statistical methods of determining the expected magnitude and frequency of natural hazards at Arthur’s Pass are greatly hindered by the absence of detailed local event data.

CHAPTER 8

THE SOCIAL IMPLICATIONS AND PREPAREDNESS ASPECTS OF NATURAL HAZARDS AT ARTHUR'S PASS

8.1 INTRODUCTION

This chapter investigates the principles of hazard management and risk reduction and applies them to the Arthur's Pass region. It also assesses the social perceptions associated with natural hazard occurrence at Arthur's Pass and reviews the effectiveness of the emergency plan currently in place in the village.

The chief objectives of this chapter are:

1. To outline principles of hazard management and risk reduction, including details of risk management integration and the relevance of the four "R's" to emergency management at Arthur's Pass.
2. To highlight common problems encountered by hazard managers when producing emergency plans.
3. To describe why an understanding of risk perception is a crucial part of natural hazard management and risk reduction and to apply this concept to the situation at Arthur's Pass.
4. To conduct a visitor survey assessing risk perceptions at Arthur's Pass and analyse the results to determine how much is known about the risk from natural hazards.
5. To discuss methods of improving hazard awareness by changing public perceptions within the Arthur's Pass National Park and village.
6. To discuss the current emergency plan at Arthur's Pass and provide recommendations for possible improvements to future plans.

8.2 PRINCIPLES OF RISK REDUCTION AND THE INTEGRATION OF HAZARD MANAGEMENT TECHNIQUES

On account of the comparatively low casualty rate directly from natural hazards in New Zealand, hazard management and mitigation have typically received little priority from authoritative organisations (Dingwall et al., 1989). More recently, however, with the increase of recreational activities and tourist numbers in the park, the hazards have become more perceptible and have been deemed of greater importance than previously.

The economy of the Arthur's Pass township and the livelihood of its occupants relies largely on the tourism industry. Accordingly, visitors to the town greatly increase the population, particularly in the summer months when conditions in the national park are at their peak. It is estimated that the overnight population within the village can rise up to one order of magnitude from 54 permanent residents to roughly 500 occupants. Accommodation for this excess of people is in a multitude of places, including Mountain House Backpackers, the Chalet Hotel, the Alpine Motel apartments, tents and campervans, houses and huts. It is therefore necessary to ensure than the hazards affecting the village are effectively mitigated. The Ministry of Civil Defence and Emergency Management uses the four "R's" principle, which aims to create resilient communities, using four methods;

- ✓ REDUCTION
- ✓ READINESS
- ✓ RESPONSE
- ✓ RECOVERY

These have been applied to the current Arthur's Pass hazard conditions in order to objectively assess where there may be opportunity for improvements to pre-existing mitigation measures. It is necessary to take into account all involved parties and determine the steps required to undertake each of the four "R's" successfully (Figure 8.1).

8.2.1 Reduction

By identifying the long-term risks to human life and property it is possible to lower the chance of emergency events occurring and reduce their potential impact (Wisner et al., 2004). There are numerous methods of risk reduction. Those that apply to the Arthur's Pass area are:

- Removing people and property from hazardous zones, using the locational approach, and relocating them to safer areas.
- Installing physical protection works, such as river stopbanks and gabions, stabilisation fencing and structural reinforcement. Funding for such works is sourced from Transit New Zealand, the New Zealand Railways Corporation, Selwyn District Council and the local residents group, the Arthur's Pass Association (Beaven, 2006).

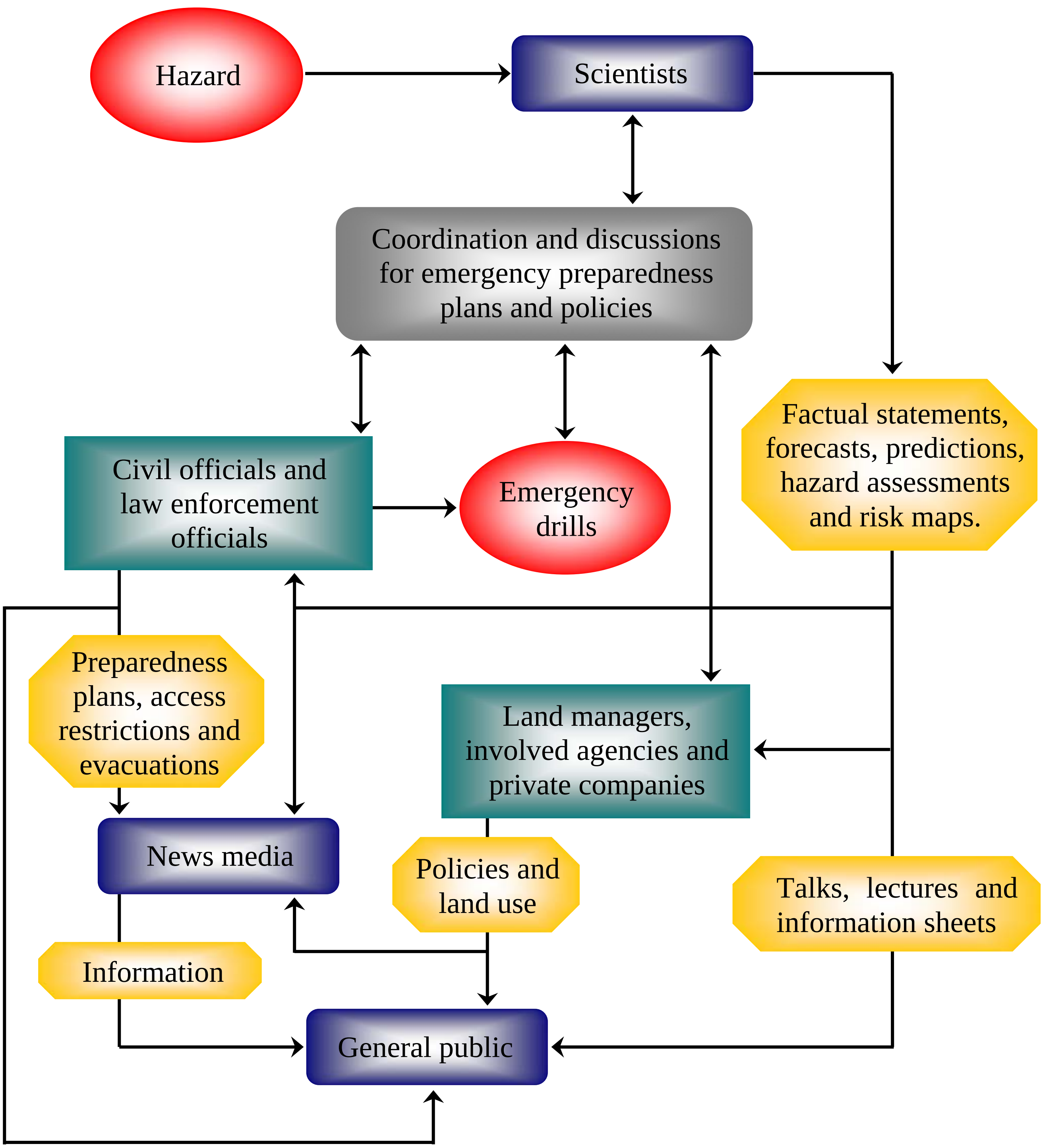

Figure 8. 1. The involvement of various organisations in hazard mitigation planning. Each group has a specific role in managing information and preparing the community for a hazard event (K. Smith, 2004).

- Employing effective land-use planning practices to restrict or prohibit development in hazardous zones.
- Decreasing town vulnerability through the implementation of better education programs for tourists, in a variety of different formats and languages.
- Increasing the number of warning signs within the village to alert people to local natural hazards.
- Obtaining welfare and medical supplies to last several days in the case of a natural disaster in which people may unable to leave the town. This coincides with the most recent Civil Defence and Emergency Management campaign (Get Thru) to make people more prepared for a disaster in order to reduce the impact of hazards on the community (Ministry of Civil Defence & Emergency Management, 2008).

8.2.2 Readiness

Readiness refers to community preparedness, through the planning and development of operational systems and capabilities in the village before an event takes place (K. Smith, 2004). The numerous hazard events at Arthur’s Pass in the past forced the residents to be very aware of the potential dangers. At Arthur’s Pass, the emergency plan stipulates that the local policeman and Department of Conservation field officer take on the primary leadership role when operating at emergency status, provided they are not injured or killed. Local residents have specific roles within the response and recovery operation.

It is essential that the village community become as self-sufficient as possible. After a regional disaster, emergency resources will be dispatched to the larger populated centres first, which will leave Arthur’s Pass with very little assistance until resources gradually become available. This may be a matter of hours to weeks, depending on the severity and magnitude of the natural disaster in question.

8.2.3 Response

Whilst the speed of large-scale emergency response within the town may be hindered by the lack of specific onsite resources, the local volunteer services that exist within the village are sufficient to cope with small-scale events. These include:

- The Arthur’s Pass Rescue and Emergency Services, which is an organisation responsible for the purchase and maintenance of rescue equipment and coordination of local volunteers and resources (Arthur's Pass Rescue and Emergency Services, 2008).

- The local branch of Civil Defence and Emergency Management that meets monthly in the old school building to keep up to date with training and emergency procedures, and which will take on a coordination and communication role following a natural disaster in the village area.
- The Arthur’s Pass Volunteer Rural Fire Force, which meets three times a month and is accountable for responding to fires, motor vehicle accidents and Civil Defence Emergencies (Arthur's Pass Rescue and Emergency Services, 2008).
- The Arthur’s Pass Police, located immediately south of the Rough Creek bridge, on top of the debris fan. The local police officer takes a leadership role in responding to emergencies and co-ordinating the response to natural hazard events.
- The Arthur’s Pass division of the Department of Conservation, which is the administrative centre for the Arthur’s Pass National Park. The field supervisor of the Department of Conservation also takes a leadership role in emergency management and response to emergency situations (Brown, 2006).

Outside resources are also available to Arthur’s Pass. The nearest medical centres to Arthur’s Pass are at Darfield (in Canterbury) and Moana (in Westland). Both are approximately one hour away by road. Ambulances come from Darfield and the response time is approximately one hour. The Westpac rescue helicopter is one of the few rescue helicopters operating in Canterbury, but several helicopter companies are available for rescue operations in the event of a major disaster. The Westpac rescue helicopter can reach Arthur’s Pass in approximately 45 minutes. Basic first aid is available at the visitor centre and the police station (SoftRock NZ, 2008a).

8.2.4 Recovery

In a best-case scenario, the most important infrastructure (such as water and food supplies, telecommunications, electricity and roads) would be repaired in a relatively short time, depending on the extent of the damage. However, there would be a significant delay in the recovery time of Arthur’s Pass if it was affected by a regional disaster. Access to medical aid and help from Civil Defence and other external organisations would be heavily delayed because their priority would focus on the populated centres such as Christchurch.

8.3 COMMON ISSUES ASSOCIATED WITH HAZARD MANAGEMENT AND RISK REDUCTION METHODS

Some of the barriers to risk mitigation are:

- The lack of hazard awareness and the underestimation of real risk from natural hazard events by both the community and government agencies.
- The use of technical language and formats in hazard investigations that make it difficult for non-experts to understand or recognise the hazards.
- The lack of detailed information on the nature and potential consequences of natural hazards and methods of practical hazard mitigation.
- Insufficient evidence of hazard data that would influence governing bodies to mitigate for risk reduction.
- The lack of coordination between organisations involved with hazard management and the community.
- A shortage of people trained in data extrapolation, hazard identification and analysis of technical information. Similarly, there is lack of people with specific welfare, rescue and emergency skills within the affected area.

Often the overall effects of a natural disaster are under-estimated because immediate loss estimates fail to take into account the social impact they have. Damaging events are typically classified according to their causes, but in order for a disaster to eventuate, specific human and economic effect thresholds must first be reached (K. Smith, 2004). The acuteness of impacts resulting from a disaster event are largely dependent on several factors. These take account of the magnitude and extent of the hazard, the initial vulnerability of the area affected and the ability of the community to remain resilient and recover from the disaster. Changing social perceptions and ensuring that the Arthur's Pass community has an appropriate level of hazard awareness is critical to the success of hazard management in the village and national park. The perceptions of visitors to Arthur's Pass village largely govern how successful the hazard mitigation programmes are.

8.4 UNDERSTANDING RISK PERCEPTION FOR HAZARD MANAGEMENT

The perception of natural hazards in society is a fundamental aspect of hazard management that can be manipulated for the purpose of risk reduction and used as a tool to implement preventative measures (Plapp & Werner, 2006). A community's vulnerability is directly proportional to how the risks are perceived and dealt with by community members. Because vulnerability is a function of human action and behaviour (Dept. of Economic and Social Affairs 2002) it is necessary to assess the community understanding of risk, willingness to accept the risk and personal preparedness in order to minimise the exposure of both tourist and resident populations at Arthur's Pass from natural hazards.

8.4.1 Measuring public perception

An assessment of the social perceptions of visitors to Arthur's Pass was carried out using an anonymous, two page questionnaire (Appendix D). Participants were selected at random in the Arthur's Pass Visitor Centre, and represented a wide range of ages, nationalities, transport modes and purposes for visiting the village.

The specific objectives of the questionnaire were to determine:

a) Whether visitors to Arthur's Pass village had any knowledge of the natural hazards in the village either before their arrival or subsequent to their visit.
b) Whether visitors had observed any plans explaining evacuation procedures in the village since their arrival.
c) If visitors were aware of any hazard mitigation measures currently in place in the village.
d) If visitors thought the hazards were well managed or if there were any improvements they felt were necessary to improve public safety and hazard awareness within the town.
e) How severely visitors rated the risk for all identified hazards in the village.
f) Whether visitors would feel confident knowing what to do if a hazard event did occur in the village.

8.4.2 Survey limitations

Limitations are inevitable in a survey of this kind, but every attempt has been made to get the most representative results possible. The survey was conducted in early March 2008. Due to the timing of the survey, participants were summer-time visitors to the park and may not have been aware of other seasonal hazards affecting the town. Consequently, this may have skewed the results slightly by downplaying the relative risk of winter hazards compared to hazards observable during the warmer months.

The number of participants in the study was lower than expected due to low visitor numbers and unfavourable weather conditions in the region at the time. Results may have a higher statistical variability but they give an adequate overview of public hazard perceptions which has been deemed sufficient for this simple, exploratory study.

The survey is only intended to give a generalised idea of the knowledge that Arthur’s Pass visitors have to the hazards. In many cases, survey participants had only just arrived in the village and had yet to make any significant observations on natural hazard issues, which they may have otherwise noticed had they been in the town longer.

8.4.3 Survey results

The survey results are expected to contribute to the revision of the emergency plan at Arthur’s Pass and work towards improving public safety within the park.

The survey results concluded that:

- Half of the participants had not viewed any information notifying them of the potential hazards at Arthur’s Pass nor did they have any prior knowledge of hazard issues in the village. Those that were aware of the risks had observed warning signs or had experienced the hazards first hand whilst visiting the town previously.
- An overwhelming number (83%) of participants had not observed any form of evacuation procedures or plans since they arrived in the town. Those that were observed were primarily in tourist lodgings and were mostly limited to fire emergency protocols.
- Almost 80% of participants were not aware of any protective measures in place to mitigate natural hazards in the village and park surrounds. Participants with knowledge of protective measures referred to avalanche shelters, warning signs and the periodic closure of some walks as the main methods of protection for visitors.
- 40% of participants thought the hazards were well managed. The other 60% were unsure of whether there were methods in place or if they were managed effectively.
- 54% of participants did not feel confident knowing what to do if a natural hazard event occurred in the village. 38% felt they could cope and would know what to do in a disaster situation and 8% were unsure whether they would know what to do during a hazard event.

- When asked if they could suggest any methods of improvement to visitor safety within the park, most participants stated that there could be more information describing the hazards and their distribution, severity and frequency.
- Participants were asked to rate ten hazards on a scale of 0 to 5 (0 representing no risk whatsoever and 5 representing very high risk). These ratings were then averaged and graded in order of the greatest perceived threat. Heavy snow and landslides were thought to be the most hazardous events at Arthur's Pass, closely followed by snow avalanches and strong winds. River sedimentation and earthquakes were identified by visitors to Arthur's Pass as the least hazardous processes affecting the village.

Observations of the community structure at Arthur's Pass confirm that there are two distinct community groups; transients and residents. The transient group is largely made up of tourists, expected to stay in the town for a few minutes up to several months. The permanent population consists of the town residents who have resided in the village for more than one year. Transient groups are largely uninformed of the presence of natural hazards and possible risk factors and do not have a good understanding of emergency procedures. Conversely, the permanent residents are well-informed and have a good understanding of the hazards, their possible consequences and what actions should be taken in an emergency.

8.5 CHANGING PUBLIC ATTITUDES AND REDUCING VULNERABILITY AT ARTHUR'S PASS

The first step in minimising community vulnerability is realising that there is a link between public perceptions and individual responses to an emergency event. However, Rogers (1997) points out that people's perceptions differ from expert perception estimates (which are based on technical calculations for magnitude and frequency) because of additional factors, such as the scale of possible events, the public's judgement and scientific understanding of the topic and whether they feel they are being voluntarily exposed to the hazards.

Reports by numerous authors such as Dingwall, Fitzharris and Owens (1989), Dunbar (2007), Espiner (1999), Gough (2000), Johnston and Houghton (1995), Plapp and Werner (2006) and Plattner, Plapp and Hebel (2006) focus on the development of public perception as an aid to improving community safety and establishing communication channels between communities, government agencies and emergency organisations. Information gained from perception studies can be applied to the development of risk communication (Gough, 2000).

Public attitudes are ultimately what govern the outcome of any emergency situation. The aim in emergency management is to alter the public perception of risk and control visitor behaviour during an extreme event in a positive way (Espiner, 1999). Lindell and Perry (1993) argue that a detailed understanding of the hazard is not necessarily crucial in order for people to be motivated enough to prepare for a natural hazard event. They must, however, believe that the hazard exists and that protective measures are required.

The findings from the tourist survey demonstrate that a small number of park visitors are aware of the risks posed by natural hazards and may even be drawn to park activities because of them. They also show that much of the public is largely unaware of any dangers until they experience or read about them. Similar observations were recorded by Dingwall et al (1989) when reviewing natural hazards and the safety of visitors in national parks around New Zealand. They also note that whilst most visitors are powerless to stop a natural event occurring, an individual's personal judgement and behaviour alters with experience, training and by various safety measures and information provided by emergency and national park managers.

Studies show that another critical factor in increasing public hazard awareness and communicating to the public about natural hazard issues is through the integration of quality education programs in high risk regions such as Arthur's Pass (Johnston & Houghton, 1995). However, the effectiveness and success of such programs is greatly reliant on the way in which the information is expressed. Giving as much information as possible to the public in the right format allows people to make the most informed decisions and better prepares them for an extreme natural event should one ever occur (Montz, 1993). Therefore, it is very important to not only have educational information available on natural hazards at Arthur's Pass but to present it in the right way so as to be effective. By highlighting the risks associated with the village and national park, visitors will hopefully modify their behaviour and subsequently lower the threat to themselves and others from natural hazards.

Research completed by Espiner (1999) into the effectiveness of signage in hazardous areas such as the Franz Josef and Fox Glaciers demonstrated that the use of hazard warning signs is also imperative in increasing public awareness of natural hazards. These results were mirrored in the Arthur's Pass survey, such that the presence of hazard warning signs was the principal form of hazard information observed by participants .

Another crucial step in achieving effective community awareness of the natural hazards at Arthur's Pass is involving the resident population in discussions, gaining their trust and proactively increasing the confidence of the community so that they will feel prepared and cope well during a disaster event. Arthur's Pass residents have been included as partners in risk communication and hazard management decision making for some time, as they constitute a large part of the emergency agencies in the village (Costello, 2008).

8.6 THE CURRENT AND FUTURE ARTHUR'S PASS EMERGENCY PLANS

The emergency plan currently in place at Arthur's Pass is modelled on the Mt. Cook emergency management plan and tends to be more of a theoretical plan rather than a practical one. Also in use is the Local CDEM Arrangements (2007) distributed by the Selwyn District Council, which is a generic plan outlining the organisational structure of any emergency response and the responsibilities of emergency agencies before, during and after an emergency situation.

Currently, there is no emergency plan employed at Arthur's Pass dealing specifically with practical approaches to emergency situations within the village and national park. Residents have requested that there be a more detailed plan describing details of several aspects of any emergency scenario, in order for the village to have the greatest level of preparedness possible (Costello, 2008). The development of a revised and specialised emergency plan is currently under way and is expected to have:

- Detailed methods of systematically searching the village following an emergency event. The village will be divided up into sections and each building will be searched one by one until that section is cleared, before moving onto the next section.
- A list of Arthur's Pass residents, their contact numbers, addresses and specialist skills so that rescue and recovery efforts can be better coordinated.
- The protocols for purchasing rescue and welfare equipment and where it would

be stored so that fewer resources have to be brought in from outside the park which may be extremely difficult after a disaster event.

- Details on the location and quantity of food supplies stored in town to help the village be somewhat self-sustainable following a disaster event.
- An outline of remedial measures to be taken for the recovery of the village after an emergency. (Costello, 2008)

Once revised, this plan is expected to be drafted and sent out to all residents for comments and further suggestions. After the final draft has been prepared it will eventually be distributed to all house and business owners in the village. The Selwyn District Council in conjunction with the Department of Conservation and other emergency organisations within the village are required to implement all necessary measures outlined in the emergency plan once it has been completed (Brown, 2006). It is expected that the production of a new emergency plan at Arthur's Pass will be more successful if it is developed and maintained as an integral part of the emergency preparedness process, which encourages open thinking and reduces uncertainty (Office of the United Nations, 1986).

There were plans to finish the revised emergency plan by mid-2008 but this is unlikely to occur because of time constraints and the resignation of the current emergency manager in the village.

8.7 RECOMMENDATIONS FOR THE REVISED ARTHUR'S PASS EMERGENCY PLAN

When preparing an emergency plan tailored specifically to the Arthur's Pass region, it is important to deal with as many aspects of preparedness as possible. The plan must distinguish between the anticipated behaviour of the hazards and the specific local factors which may affect responsive actions whilst precisely defining the situations it was designed for (Office of the United Nations, 1984).

The United Nations (1986) asserts that several essential components make up a successful and operational emergency plan.

1. It should clearly state what the assumptions are on which the plan is based, and define the goals that are expected to be achieved as part of the plan development.

2. It should discuss the organisational aspects of the plan, including responsibilities for project management, liaison, administrative support and maintenance of the plan once it is established.
3. It should link agencies involved in the emergency process and acknowledge the input and support of other organisations and local groups during a disaster phase.
4. It needs to consider the technical aspects of emergency preparedness to help with decision making.
5. It should outline strategies for public education and training through information programmes and exercises.
6. It should undergo regular maintenance and revision so that it meets its objectives and effectively manages the natural hazard threat to the Arthur's Pass community.

Possible recommendations for future planning and development to improve operational systems and emergency procedures at Arthur's Pass are:

- Include all hazards in emergency managements strategies, however insignificant, and be prepared for multiple hazard scenarios in a given time period.
- Include and plan for hazards with low risk yet high consequence (such as landslide damming and high magnitude earthquakes) as part of a town's hazard management program (Yetton, 2000).
- Use hazard maps as a way of clearly and easily conveying hazard information to government organisations, local bodies and the public.
- Aim to increase the quantity of emergency equipment and resources stored within the village so that fewer supplies will be required from other communities during an emergency.
- Increase current public awareness schemes and ensure evacuation procedures are clearly legible and placed in obvious areas that have high foot traffic.
- Prepare welfare kits to be stored in case of an emergency, particularly for transient guests to the village, who are unlikely to come prepared for a natural disaster event.
- Revise land use zones and implement changes (either structural reinforcement or relocation) to buildings likely to be affected by natural hazards within the next 50 to 100 years.
- Increase the number of warning signs in areas affected by natural hazards around the village and within the national park to better prepare visitors for possible dangers.

It is clear from this evaluation of hazard mitigation at Arthur's Pass that there are definite opportunities for improvement to community safety and risk reduction both in the village and within the Arthur's Pass National Park. Progress towards the creation of a successful mitigation program at Arthur's Pass relies on effective partnerships between government agencies, the community and local organisations. Such partnerships should include bodies from all governmental levels such as Environment Canterbury and the Selwyn District Council. The local Civil Defence and Emergency Management (CDEM) branch will be responsible for immediate action following a natural disaster and need to be fully updated and informed on the local hazard status at Arthur's Pass. Other organisations within the community such as the Arthur's Pass Rescue and Emergency Service, the Arthur's Pass Volunteer Rural Fire Force, the Department of Conservation and local business owners play a significant role in ensuring the response and recovery of the village during the post-disaster period is as efficient as possible.

8.8 SUMMARY

Hazard management is a complex process and requires the coordination of many different factors before, during and after a natural disaster. Social perceptions are a very important consideration and can greatly affect the success of an emergency plan. The emergency plan at Arthur's Pass should be revised with this in mind and be adapted to specifically deal with the Arthur's Pass region and the local community.

The outcomes of this section demonstrate that:

1. Natural hazards in New Zealand have been given greater importance in recent years due to an increase in the frequency, severity and economic cost of hazard events around the country. This scenario is also evident at Arthur's Pass, where an increase in number of recreational users of the national park and village has expanded the risk from natural hazards in the region.
2. The four "R's" concept of hazard mitigation adopted by the Ministry of Civil Defence and Emergency Management in New Zealand has been applied to Arthur's Pass and identifies which aspects of emergency management are sufficiently managed and areas that might be at risk and are in need of further mitigation. It is suggested that the village is somewhat prepared for a disaster, but there may be issues in the response and recovery phases of a disaster event.

3. Some of the barriers to risk reduction, including the underestimation of the real risk posed by natural hazards in the village, the lack of coordination between governing and emergency agencies, the lack of detailed information on hazard areas and potential consequences of a hazard event all contribute to the risk factor within the village and national park. These issues have been addressed during the development of recommendations for the improvement of the Arthur’s Pass emergency plan.
4. Public perceptions are an essential aspect of hazard management and in order to analyse the level of awareness of natural hazards and emergency plans of visitors to the village, a questionnaire was distributed within the Arthur’s Pass Visitor Centre. The results suggested that few participants had observed hazard evacuation plans or warning signs and most participants underestimated the risk posed by several hazards, particularly earthquakes and erosion. Over half of those surveyed said they would not feel confident knowing what to do in an emergency.
5. Changing public perceptions with a view to reducing natural hazard risk is possible through several means. Appropriate education programmes and information supplied in various locations is one of the best methods of increasing hazard awareness. Studies show that the installation of warning signs in hazardous zones is extremely useful, and involving the community in the development of emergency plans has proven to increase confidence and improve emergency preparedness.
6. The emergency plan currently in place at Arthur’s Pass has not been specifically tailored to the village. A revised plan is currently in development and will contain explicit details on systematic search methods, contact details for village residents and a list of their strengths and previous training, protocols for the purchase and storage of rescue and welfare equipment and an outline of remedial steps for the recovery of the village after an emergency.
7. It is important that the future emergency plan reflects the Arthur’s Pass situation and effectively reduces the hazard risk. There are several essential components of the emergency and preparedness plan development. These include stating the assumptions upon which it is based, outlining the objectives and organisation of the plan and the responsibilities of organisations involved in the emergency effort, linking emergency agencies and local groups so emergency procedures are coordinated, discussing the technical aspects of the plan and outlining education strategies that will aid in risk reduction. Based on these principles, a number of recommendations for the future emergency plan have been presented.

CHAPTER 9
SUMMARY AND CONCLUSIONS

9.1 RESEARCH OBJECTIVES AND METHODS

The principal aim of this research was to assess the vulnerability of the Arthur's Pass township to natural hazards in order to assist governing bodies and local agencies in making informed decisions about emergency planning and mitigation in the village.

The steps taken to achieve the aim have been:

1. To conduct a detailed analysis of the four hazard types identified in the village; seismic hazards, meteorological hazards, mass movement hazards and fluvial-related hazards.
2. To collate the hazard analysis information and use it to construct a series of hazard maps showing potential risk zones based on historical events and indicators identified in the field.
3. To examine methods of risk reduction and their potential for application to the Arthur's Pass region.
4. To investigate the public perception of risk from natural hazards within the village area.
5. To evaluate the current emergency plan at Arthur's Pass and offer suggestions for improvements to revised versions of the plan.

Initially a review of the literature was completed to identify possible shortcomings in previous hazard and geological studies of the Arthur's Pass region. This process revealed that much of the previous research focuses on slope instabilities along State Highway 73 and through the Otira Gorge. A number of studies also investigate the complex structural conditions present in the region and analyse historical Arthur's Pass earthquakes to better understand tectonic processes. Detailed assessments of natural hazards specific to the village area were, for the most part, absent from the literature, which demonstrates the need for such a thorough investigation to be undertaken. The result of this work (some of which is presented in the form of hazard maps) aims to indicate where the hazards exist and what steps can be taken to minimise them. Historical events have been relied on heavily to illustrate potential hazard issues.

9.2 HAZARD IDENTIFICATION AND ANALYSIS

The four hazard assessment sections (Chapters 3 to 6) comprised the main body of this research. Each chapter combined information from the literature, in-field investigations and historical data to assess the vulnerability of the Arthur's Pass community and its infrastructure to natural hazards sourced both locally and distally. The hazards identified at Arthur's Pass have complex interrelationships and often influence the location and initiation of other hazard events throughout the Arthur's Pass National Park.

9.2.1 Seismic hazards

- Arthur's Pass is located at the junction of the Alpine Fault and the Marlborough Fault System. As a result, the region experiences the seismic traits of both fault systems. The proximity of the township to such major plate boundary faults results in the capacity for fault ruptures to produce shaking intensities up to MM X within a 150 to 500 year return period.
- Shallow earthquakes generated in the Arthur's Pass region produce a greater seismic hazard because they tend to generate shorter duration but more intense ground shaking than other locations in the South Island. These shallow earthquakes have the ability to amplify the hazard impacts within the village and negatively influence response and recovery efforts during an emergency phase.
- The high number of historical earthquakes affecting the Arthur's Pass township caused by both regional and local fault ruptures indicates that there is a moderate to high risk from known fault traces. There is also a constant background risk from unidentified or untraceable faults within close proximity to the village that cannot be factored into precise probability calculations. Whilst the exact timing and location of the next earthquake is unknown, the impacts it may have on the village can be forecasted to allow for appropriate emergency management to take place.
- Major issues with seismic hazards include the risk to lives, property and essential infrastructure, but there are few mitigation methods for seismic hazards other than being sufficiently prepared. In this case, the hazard cannot be reduced but the risk can be managed with the employment of effective mitigation solutions.

9.2.2 Meteorological hazards

- The weather patterns at Arthur’s Pass comprise mostly warm, north-westerly, rain-bearing winds alternating with strong, cold southerlies. Summer thunderstorms associated with anti-cyclonic periods can generate heavy rain, hail, lightning and strong winds. During the cooler months, heavy snowfall and avalanches are hazards throughout the village and Arthur’s Pass National Park.
- Meteorological hazards are generally high frequency, low magnitude events and primarily act as a trigger or catalyst for other hazard types, such as landslides, minor slips and flooding. Weather-related hazards tend to be a greater risk to users of the national park than people within the village boundaries, because of their higher degree of exposure. These hazards can be forecast to a certain extent and there are several mitigation methods available to treat the hazards and reduce the impacts they have on the Arthur’s Pass community.
- Climate change and global warming is predicted to have a considerable effect on weather patterns, by increasing the unpredictability of extreme events in the Arthur’s Pass region. Temperature averages, rainfall and evaporation are all expected to increase, and future projections estimate that snow patterns and wind conditions will become more extreme. Determining the precise reactions of the Arthur’s Pass environment to global warming is very difficult, which increases the importance of having effective hazard management in the village.

9.2.3 Mass movement hazards

- Landslides, rockfalls and minor slips are the most common and widespread mass movement hazards identified in the area. There is also evidence for the occurrence of debris flows in the Rough Creek, McGrath Stream and possibly Wardens Creek tributaries despite there being no recorded debris flow events in the area since European settlement.
- Storms and seismic shaking are the primary triggers for mass movements. Intense rainfall and slope instabilities have a strong correlation in the Arthur’s Pass region, with both occurring frequently; up to several times a month. Conversely, large landslide deposit distributions can be used to infer fault locations.

- The incidence of mass movements within the national park has severe implications for the recreational users of the park and for State Highway 73, which is prone to blockages and closures from slope failures on a regular basis.
- Mass movements can potentially affect fluvial hazards by adding material to the drainage network, which may exacerbate erosion and aggradational processes and cause damage within the village. Large-scale, catastrophic mass movements are also a potential threat at Arthur's Pass and may generate landslide damming, or large-scale aggradation and erosion of the Bealey River bed on which the village is sited. In many cases an event of this magnitude cannot be prepared for, other than having an prompt evacuation plan in place that will remove the public from the risk zone.

9.2.4 Fluvial-related hazards

- Numerous tributaries contribute to the Bealey River catchment, several of which flow through the village area. Flooding, riverbed erosion and aggradation, and channel avulsion are the fluvial-related hazards at Arthur's Pass, and all have major implications for the village and its community.
- Flooding of the Bealey River occurs in the village area up to several times a year, occasionally inundating houses along Crusher Loop. Further opportunities for fluvial-related damage are in the form of surface flooding due to urban drainage systems failing, landslide damming, channel avulsion and encroachment of the village area, and the building up of alluvial fans. Most of these hazards are progressive and take some time to occur, which gives hazard managers the chance to mitigate the hazards and reduce the risk to the village, thereby decreasing its vulnerability.
- Flooding is almost always connected to intense rainfall, and it cannot usually be predicted more than a few hours in advance. Aggradation, erosion and channel avulsion may be more predictable but it can be difficult to employ long-term mitigation measures for these hazards without disturbing the balance of the fluvial system and making the problem more severe.
- Flood-protection measures, such as stopbanks and gabions, have been installed along the Bealey River and Rough Creek banks to prevent floods entering the developed area and damaging properties. Several of these mitigation measures have not been adequately maintained and may not provide good enough protection from floods and debris flows in the future.

9.3 HAZARD MAPPING AS AN AID TO RISK REDUCTION

The value of hazard mapping is to provide a clear means of conveying hazard information to the public, government organisations and other involved agencies both at Arthur's Pass and in the wider Canterbury region. Three maps were developed that show hazard events of >2%, 2%-0.2% and <0.2 % annual exceedence probabilities (0-50, 50-500 and 500+ year average return periods respectively). Some hazards, such as mass movements, flooding and erosion and aggradation increase in magnitude and severity over longer time periods. By contrast, fault return periods are unconstrained but considered to be constant so do not vary over the three time intervals. Snow avalanches and meteorological hazards are controlled by changes brought about by the seasons, climate change and climatic phenomena such as El Nino and the Interdecadal Pacific Oscillation (IPO), which makes prediction on their future behaviour and accurate hazard mapping difficult. Consequently, snow avalanche zones remain unchanged with time scale and meteorological hazards have been omitted from all three maps.

Many of the vulnerable hazard areas have been mapped using historical data and previous hazard areas to indicate zones of future weakness, assuming that the past is the key to the future. The maps illustrate the high vulnerability of the whole Arthur's Pass village because of its location within a very confined area on the Bealey River floodplain. Large-scale mass movements have the potential to dam tributaries of the Bealey River, which would have catastrophic impacts on the village. An event of this magnitude is expected to have a long recurrence interval, and is illustrated on the <0.2% (500+ year) map.

Also, both regional and local hazards have been accommodated on the maps because the natural hazards at Arthur's Pass take place over a variety of different temporal and spatial scales. Subtle changes detected in the fluvial network and small-scale mass movements are able to be shown on the local map, which provides greater detail for emergency manages and ultimately assists in reducing the risk from natural hazards at Arthur's Pass.

9.4 PUBLIC RISK PERCEPTIONS AT ARTHUR'S PASS

Public perceptions were assessed at Arthur's Pass using an anonymous visitor questionnaire; results are discussed in Chapter 8. The survey found that most people visiting the village were not aware of the hazards, or thought they did not represent a high risk, and a large proportion of participants said they would not feel confident knowing what actions to take in an emergency situation. Heavy snow and landslides were thought to be the most hazardous events, and river aggradation and earthquakes were rated as the least hazardous events at Arthur's Pass. Improvements to public perception and hazard awareness can be achieved by education schemes and providing more detailed information about the specific risks from natural hazards in the Arthur's Pass region. Installing warning signs and involving the community in emergency planning can also have a positive effect on public hazard perceptions, thereby reducing the vulnerability of the village.

9.5 EMERGENCY PLANNING AT ARTHUR'S PASS

An evaluation of the current emergency procedures and organisational structure of hazard management at Arthur's Pass. It revealed several areas which require further development and improvements. Arthur's Pass village is currently using a version of the Mt. Cook emergency plan and the Selwyn District Council's Local CDEM Arrangements (2007), as there is currently no specific emergency response plan for the township. A revised plan specifically for the Arthur's Pass village has been on the agenda of the village emergency managers for the last two years. It is anticipated that the new emergency plan will contain details on search methods for the village area, contact information for residents and details of their specialist emergency and rescue skills, in addition to lists of equipment and welfare supplies stored for use in emergency situations.

Several recommendations were included for the future revision of the Arthur's Pass emergency response plan. It is suggested that the future plan include details on all hazards, however insignificant, and also prepare for low magnitude, high consequence events as part of the town's emergency management program. Stockpiling welfare kits and emergency equipment is considered paramount to improve response and recovery efforts during and after a disaster event. Other recommendations advised on the continued involvement of the Arthur's Pass residents, the implementation of education schemes and land use planning as an aid to producing a successful emergency response plan.

The lack of an emergency response plan for Arthur's Pass is contributing to the vulnerability of the village as it reduces the effectiveness of preparedness, response and recovery actions before, during and after a disaster event. Ideally, a specific emergency plan will enable emergency efforts to be better coordinated and executed to ultimately reduce the natural hazard risk to residents and visitors in Arthur’s Pass.

9.6 VULNERABILITIES AT ARTHUR’S PASS

The main aim of this research was to conduct a vulnerability assessment, in both scientific and social terms, to determine risk zones and identify aspects requiring development in order to progressively reduce the risks that natural hazards present at Arthur’s Pass. Vulnerability arising from natural hazards takes several forms at Arthur’s Pass. The social aspects of vulnerability are examined in Chapter 7 and 8 which discuss the impacts of natural hazard events on the community. The main vulnerabilities in the village affect people, property and infrastructural elements. Damage to the village infrastructure is a major issue because it affects the town’s ability to provide essential services and continue functioning.

The Civil Defence and Emergency Management’s system of risk reduction using the four “R’s” was applied to the Arthur’s Pass conditions in Chapter 8. The process identified several areas with potential for improvement. Natural hazards can be reduced using physical protective methods and appropriate land use designation, as well as through the implementation of better education schemes and the distribution of information about the hazards. There is a lack of information available for visitors to the park, and as a result they are not as informed as they could be. Additionally, physical protection works require more maintenance if they are to provide sufficient protection from natural hazards in the future.

Preparing the community for a disaster is also paramount in reducing the vulnerability of the community through the planning and development of operational systems and programs to deal with an emergency should one occur. Arthur’s Pass is not adequately prepared for a disaster event, and would rely heavily on outside organisations for assistance in a post-disaster phase. Possibly the most critical vulnerability is the township’s lack of self-sufficiency. During a regional disaster, Arthur’s Pass is likely to be isolated from other areas and will probably not receive assistance and supplies from outside organisations for some time. Improvements to the readiness of the community include the purchase and storage of welfare items and emergency equipment and the use of a well-practiced emergency response and evacuation plan.

The response of the community in an emergency situation is largely dependent on the coordination and efficiency of emergency agencies and government organisations, so producing an up-to-date, adapted version of an emergency plan should be the highest priority for Arthur’s Pass emergency managers. The more organised and practiced these agencies are, the greater the success of response actions and the lower the vulnerability of the township.

Finally, the recovery of the village in a post-disaster phase is greatly controlled by the success of the reduction, readiness and response efforts before and during a hazard event. The vulnerability of the village is expected to decrease through the implementation of these risk reduction measures, which will greatly benefit the village and its community in the future.

9.7 CONCLUSIONS

1. Prior to this study, there was a lack of detailed natural hazard information for the Arthur’s Pass region.
2. The most significant natural hazards affecting the township are earthquakes, landslides, debris flows, rockfalls and river flooding and erosion. Many of the identified hazards are interdependent, and act as a trigger or catalyst for other hazard events.
3. Hazard maps for events of >2%, 2%-0.2% and <0.2 % annual exceedence probabilities (0-50, 50-500 and 500+ year average return periods) demonstrate that future hazards will take place over a variety of temporal and spatial scales, some with serious consequences on the village.
4. There is potential for several catastrophic events to take place within the Bealey Valley, as a result of landslide damming, flooding and high intensity fault ruptures.
5. Climate change and global warming will affect weather patterns and increase the unpredictability of natural hazards in the Arthur’s Pass region.
6. Vulnerabilities at Arthur’s Pass are evident in social, structural and infrastructural elements of the village. Improvements to the reduction and readiness of the village for natural hazards are required to reduce the town’s vulnerability.
7. The emergency plan for Arthur’s Pass requires modifications to include specific details, including:
    - resident contact information and specialist skills,

- response procedures,
- land use planning,
- preparedness aspects such as arrangements for the purchase, storage and use of welfare and emergency equipment to be used during a disaster.

9.8 RECOMMENDATIONS FOR FUTURE WORK

This study was by no means exhaustive and was limited by the availability of historical data, the accessibility of field areas and the lack of an in depth investigation of the geomorphic environment. There is great potential for further research in the Arthur's Pass study area:

1. It is recommended that an in depth investigation of slope stability for various slopes within the Arthur's Pass National Park should be undertaken in an attempt to expose previously unnoticed weaknesses in the mountains surrounding the township.
2. The incidence and timing of debris flow events in the Bealey Valley may require further evaluation as the analysis of previous debris flows at Arthur's Pass was severely limited by the lack of evidence and recorded data. The dating and detailed mapping of debris surfaces was considered beyond the scope of this study but is a good topic for research in the future.
3. A hazard vulnerability assessment of similar structure as this research would be of use for the Otira village (14km north of Arthur's Pass) as problems caused along the highway and within the Otira township would have consequences on the effectiveness of Arthur's Pass emergency procedures. It may be possible for the two villages to work simultaneously to progressively reduce the vulnerability of both villages. Because in many ways the towns have very similar characteristics, it would be necessary for the Otira village to implement risk reduction methods also.

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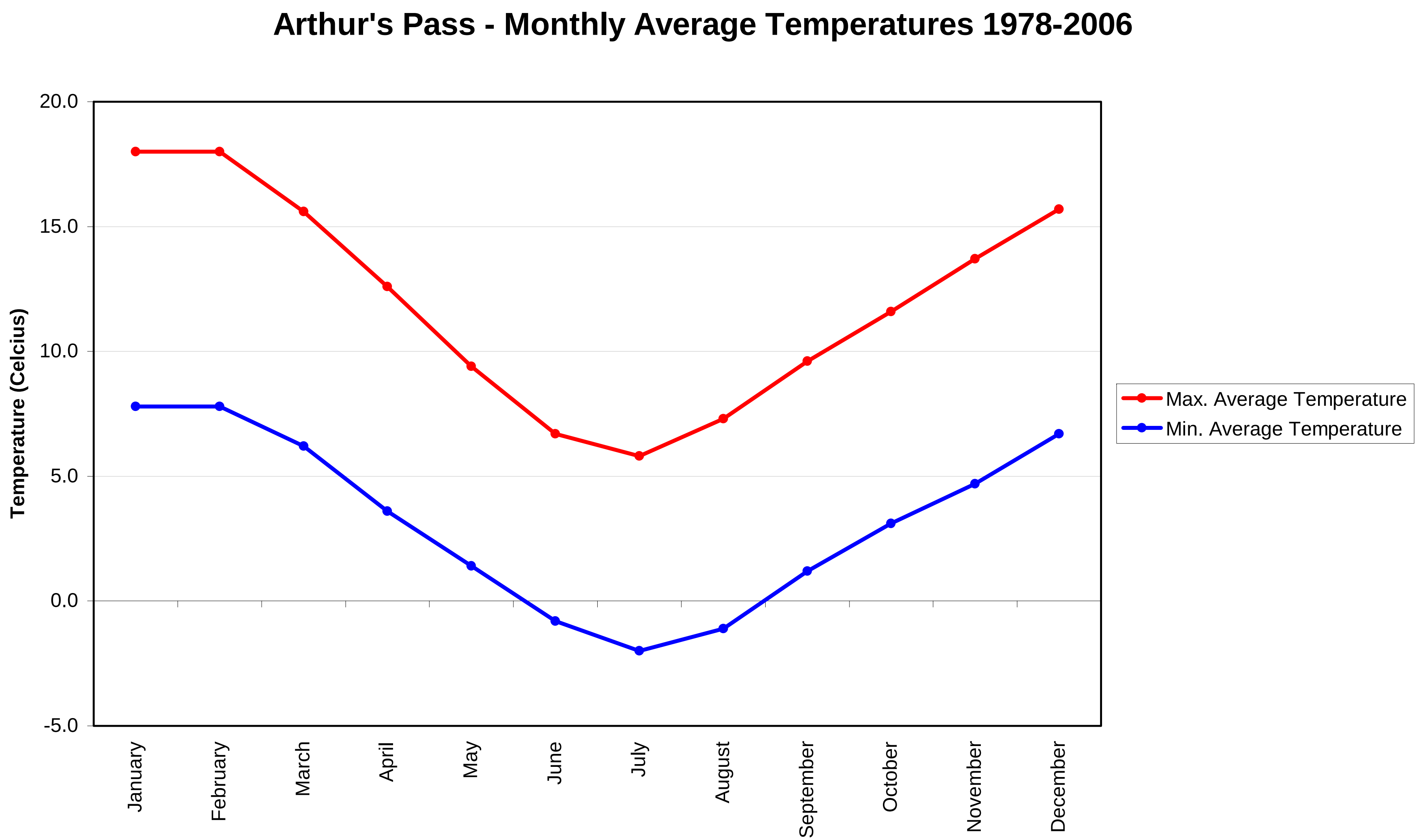
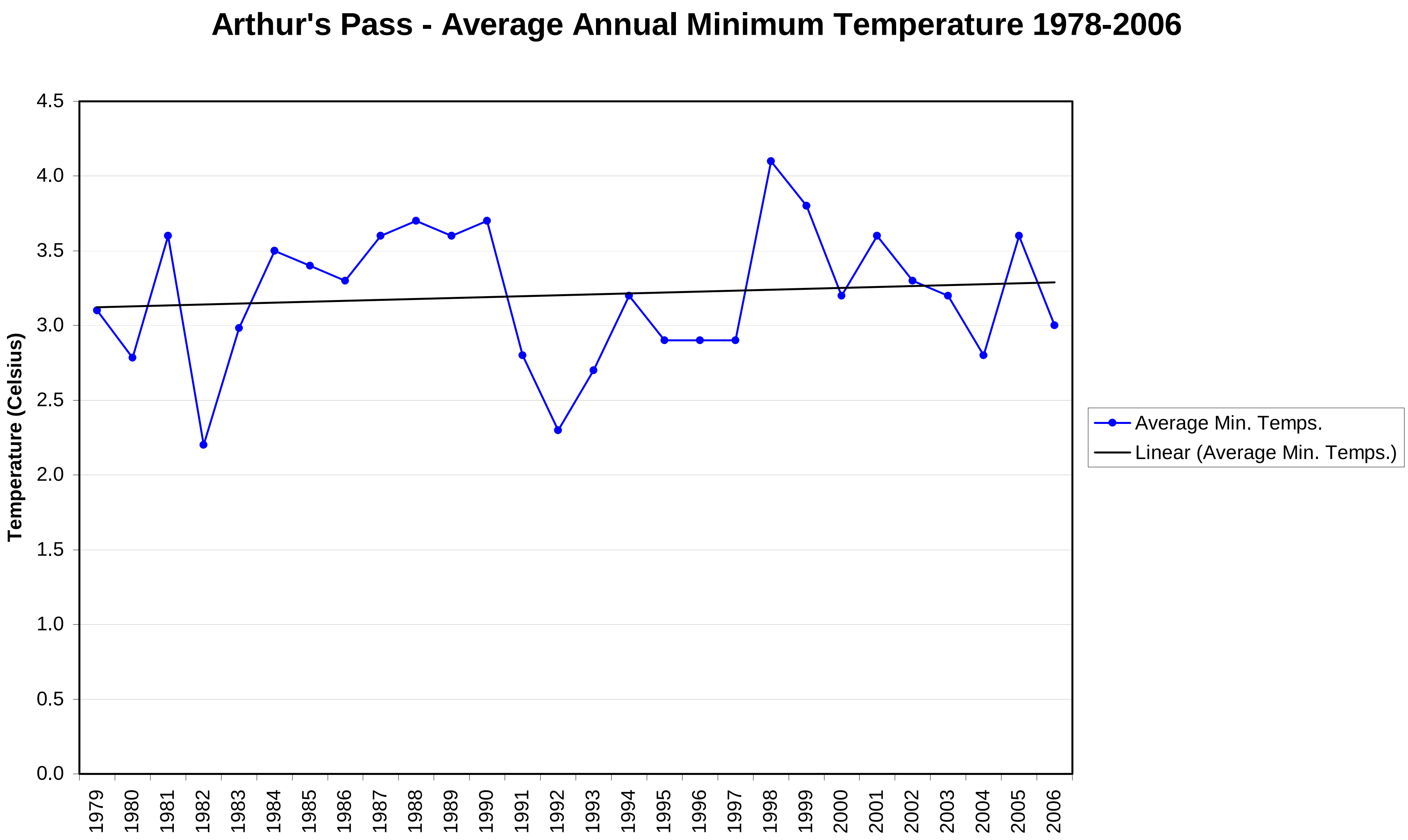
APPENDIX A

Arthur’s Pass Climate Data

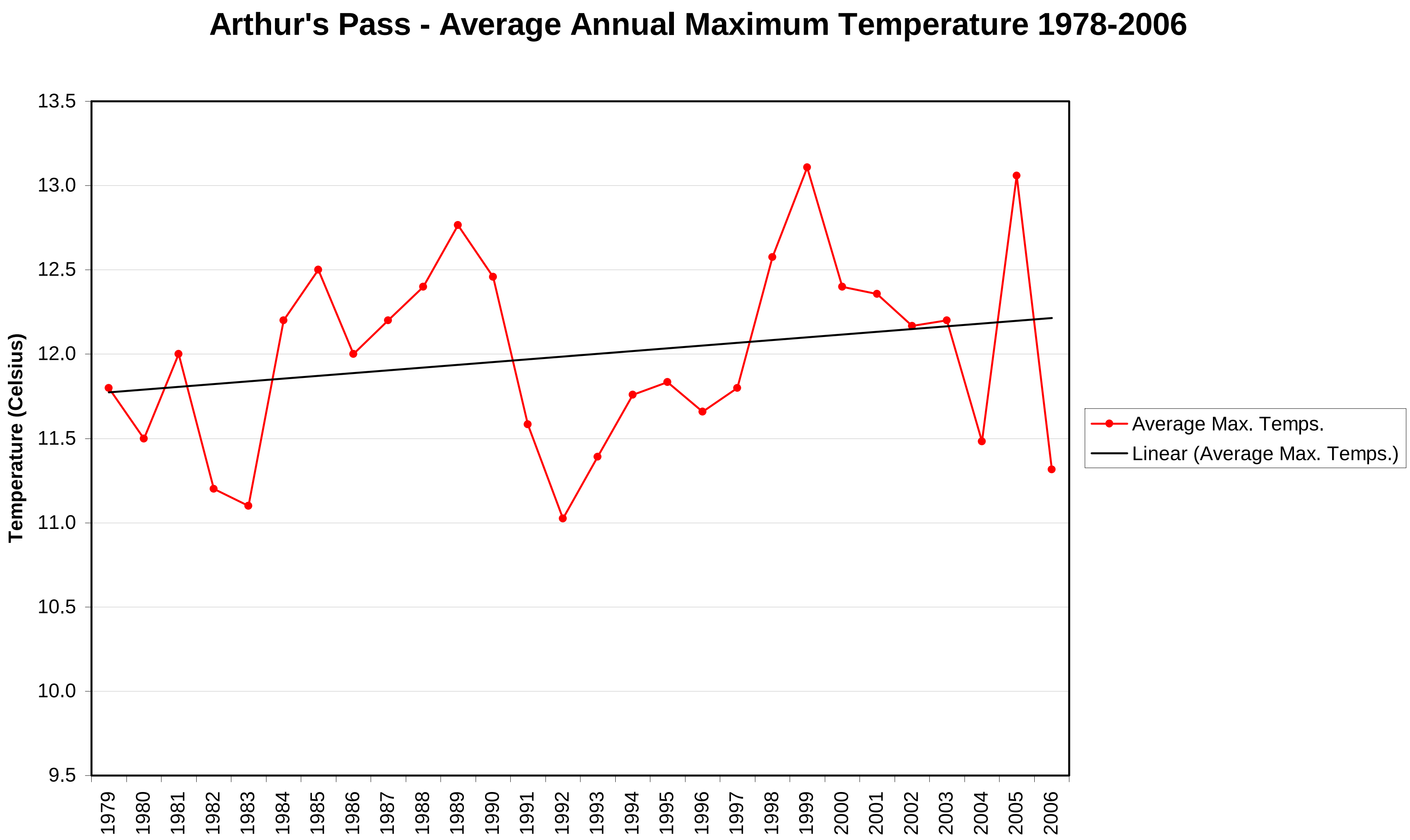
This appendix shows the short-term trends in climate data for the Arthur’s Pass region, outlined in Chapter 2 and discussed further in Chapter 4. Temperature data from 1978 to 2006 were used to graphically represent the average monthly minimum and maximum temperatures, and the maximum and minimum average annual temperature. Rainfall data from 1955 to 2006 were used to show rainfall days per year, monthly rainfall averages, yearly rainfall averages and yearly rainfall for each month (NIWA, 2007).



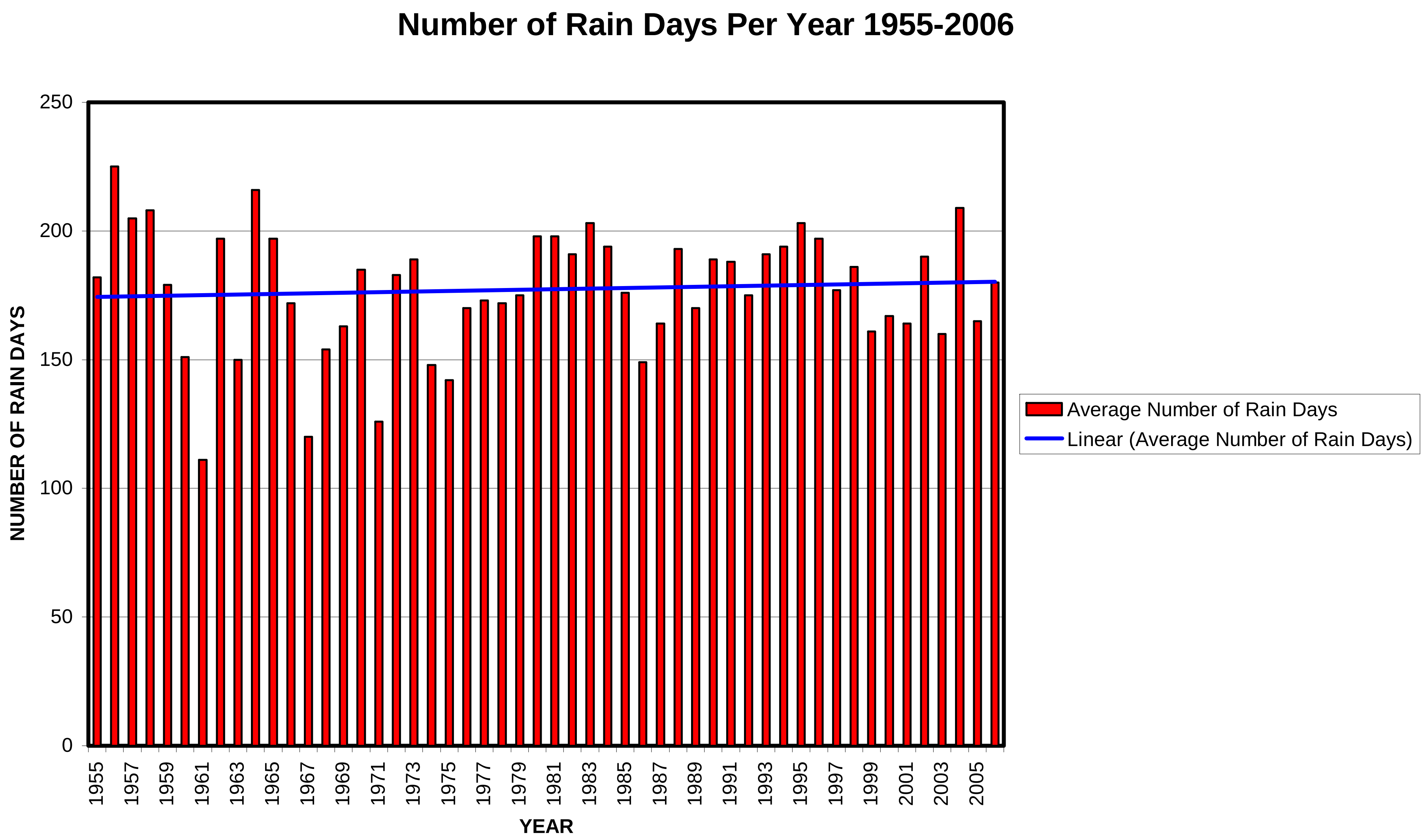
Appendix A. 1. Monthly average minimum and maximum temperatures at Arthur's Pass village from 1978 to 2006 (NIWA, 2007).



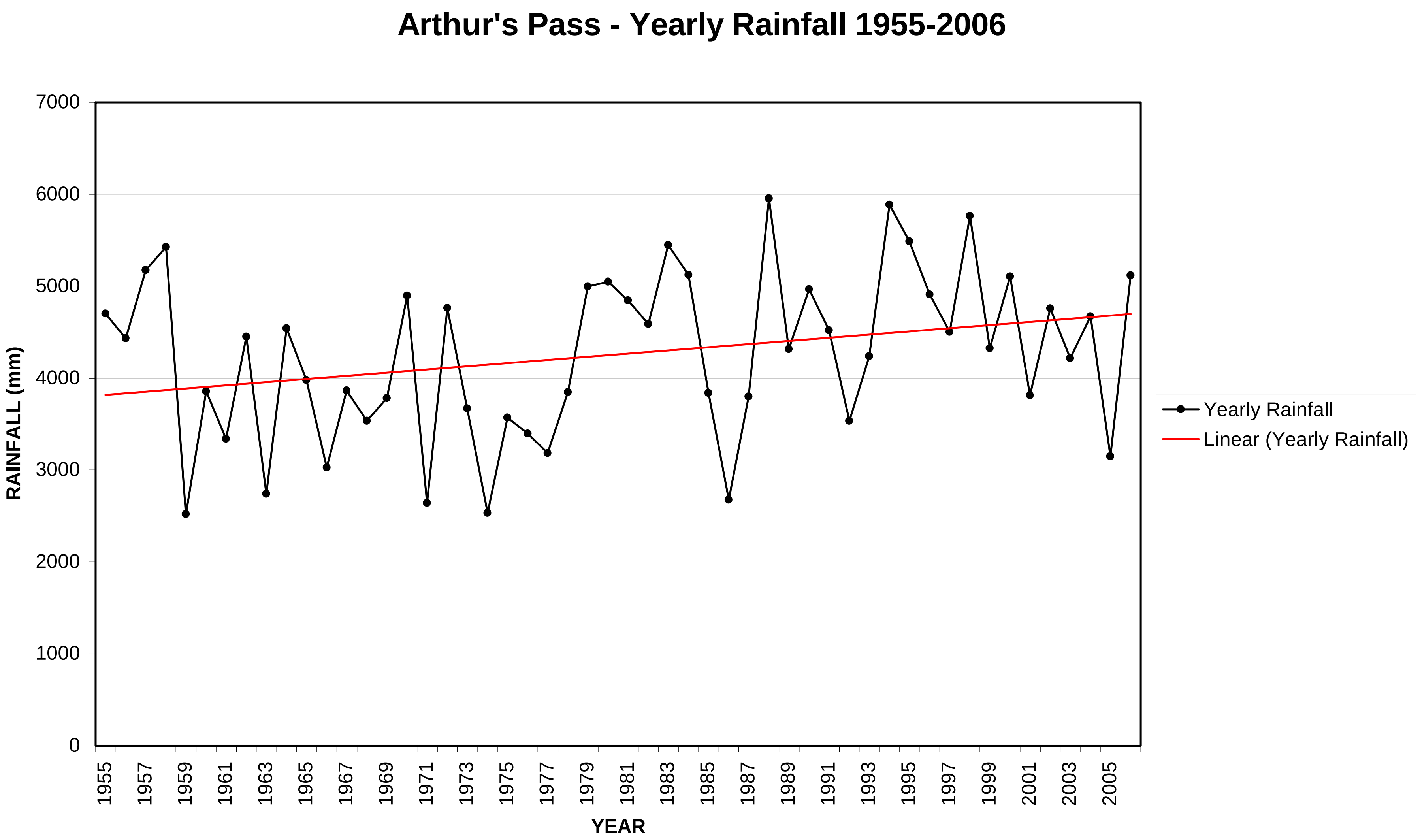
Appendix A. 2. Average annual minimum temperatures at Arthur's Pass village from 1978 (incomplete year) to 2006 (NIWA, 2007).



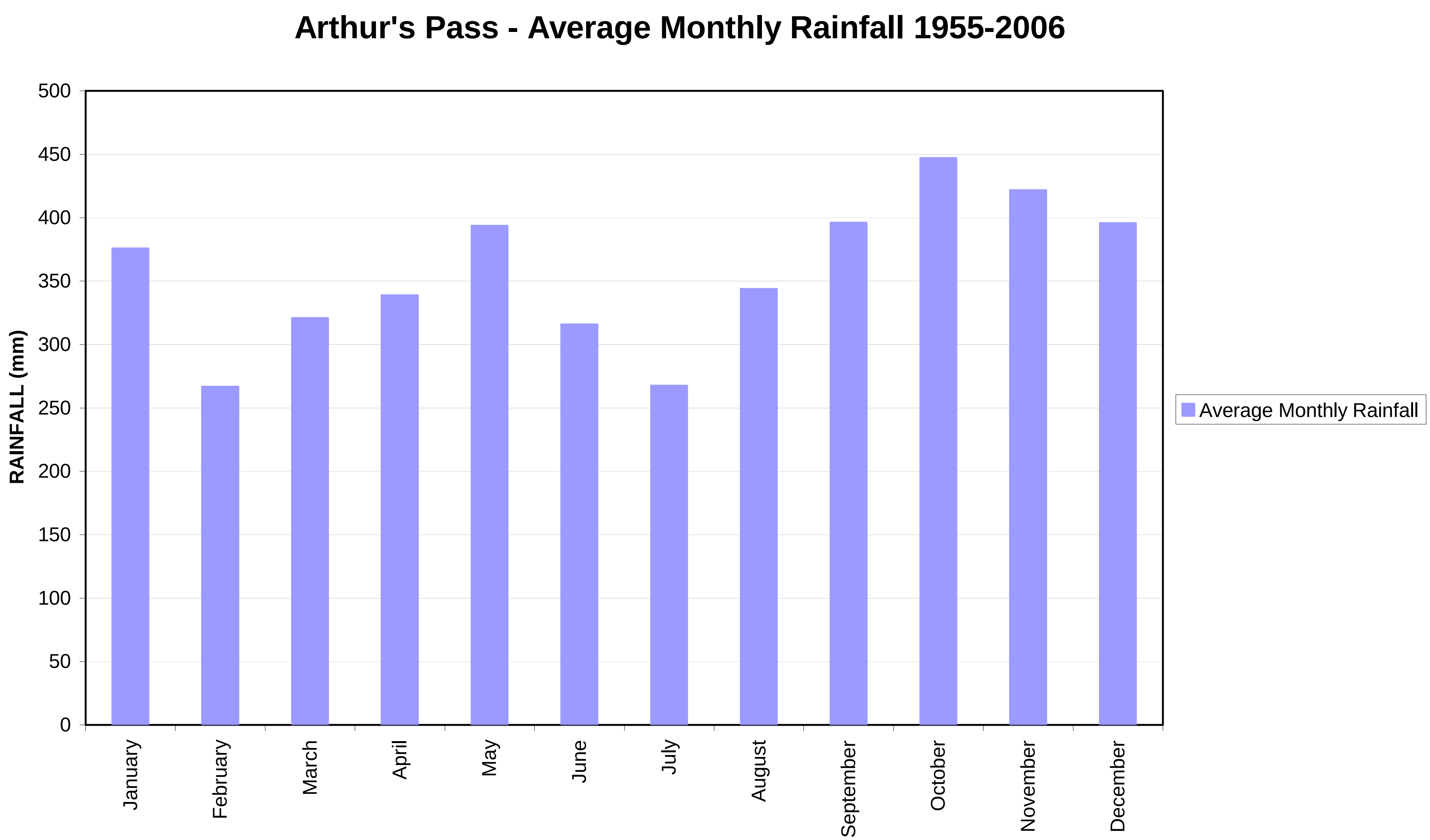
Appendix A. 3. Average annual minimum temperatures at Arthur's Pass village from 1978 (incomplete year) to 2006 (NIWA, 2007).



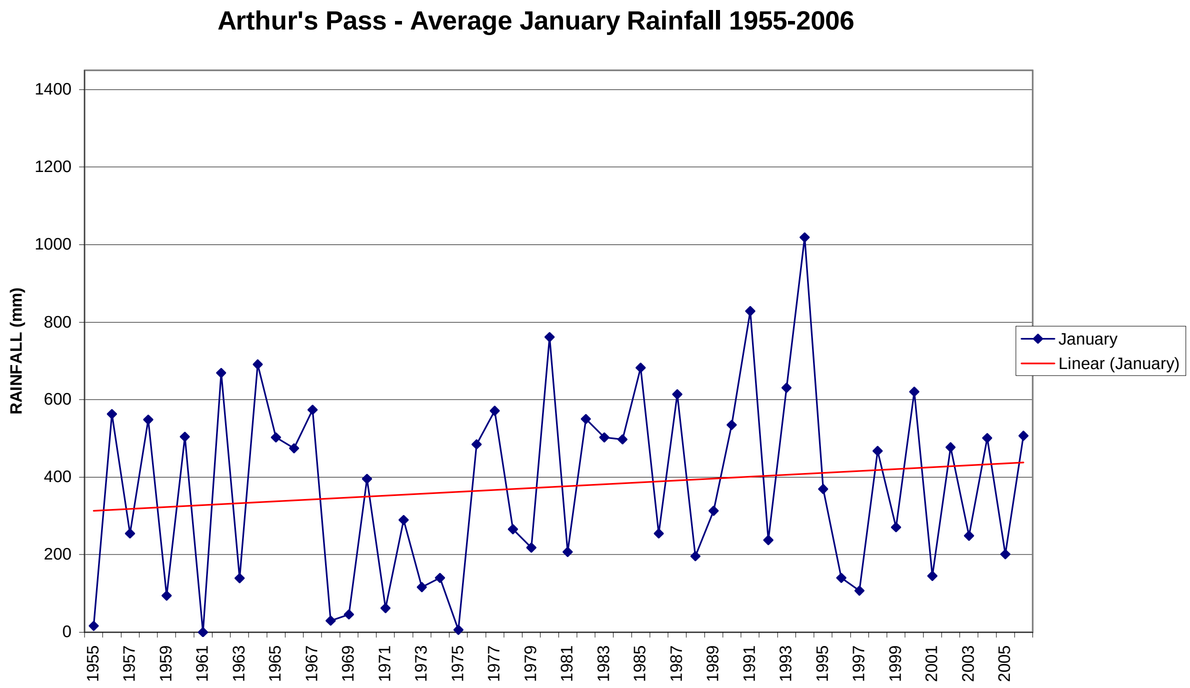
Appendix A. 4. The number of rain days at Arthur’s Pass each year from 1955 to 2006 (NIWA, 2007).



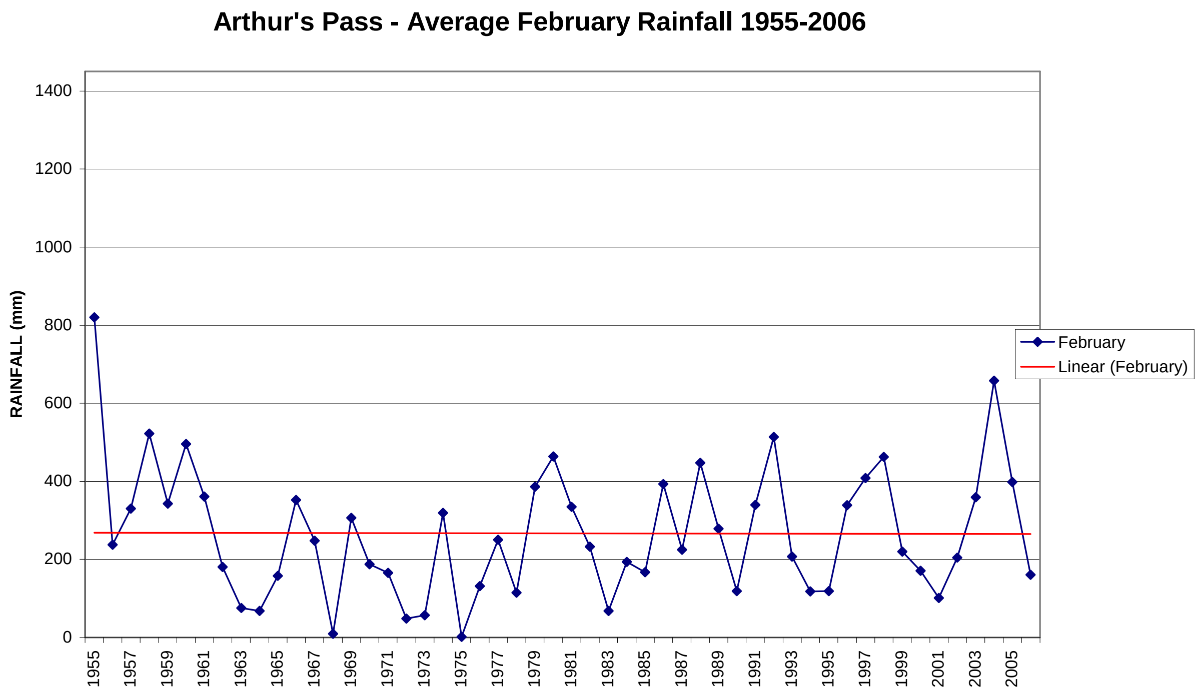
Appendix A. 5. The average annual rainfall at Arthur's Pass from 1955 to 2006, and the trend showing an increase in annual rainfall during this period (NIWA, 2007).



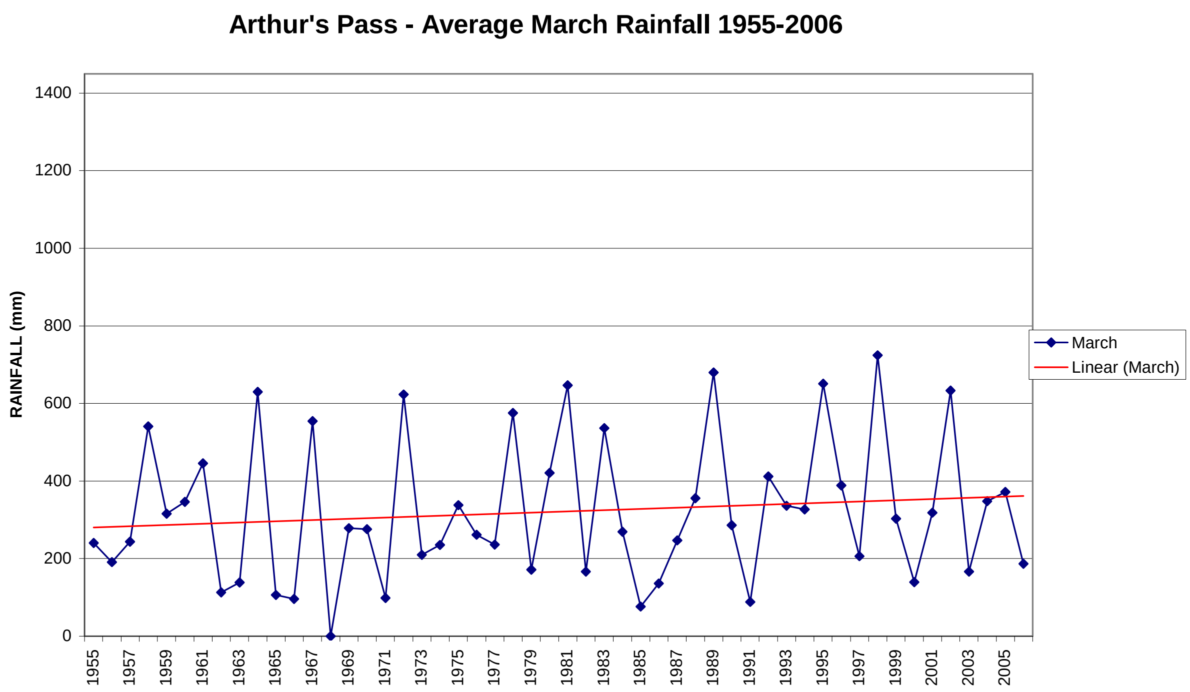
Appendix A. 6. The average monthly rainfall at Arthur’s Pass from 1955 to 2006 (NIWA, 2007).



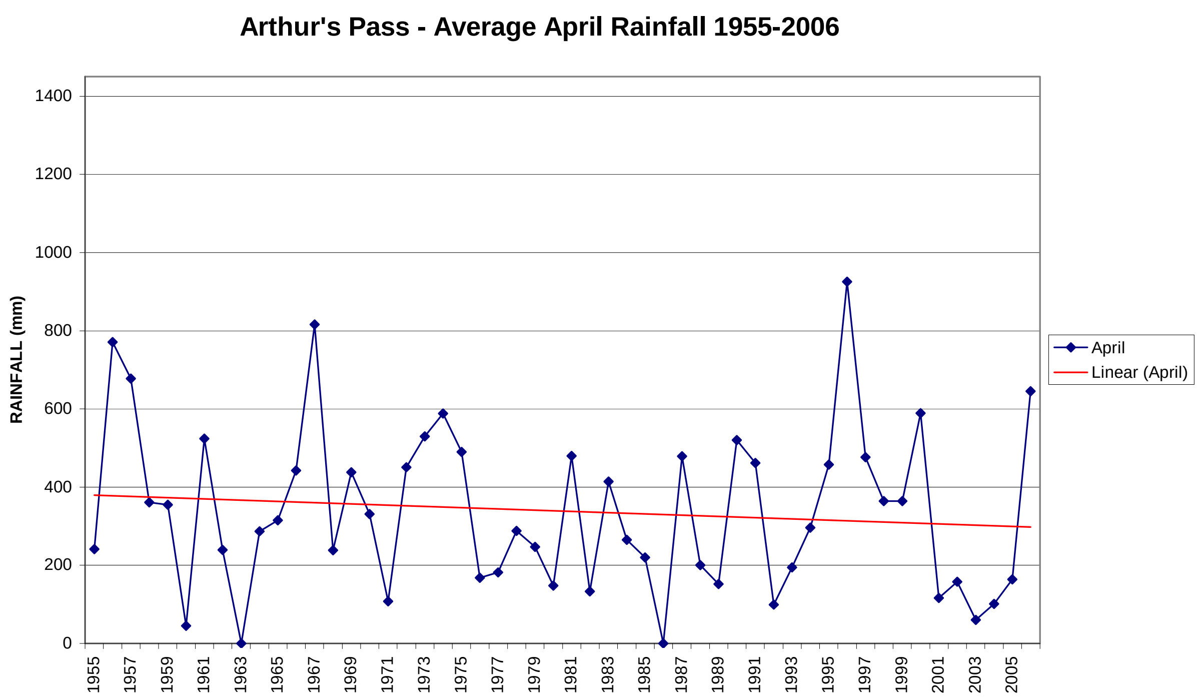
Appendix A. 7. Average January rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



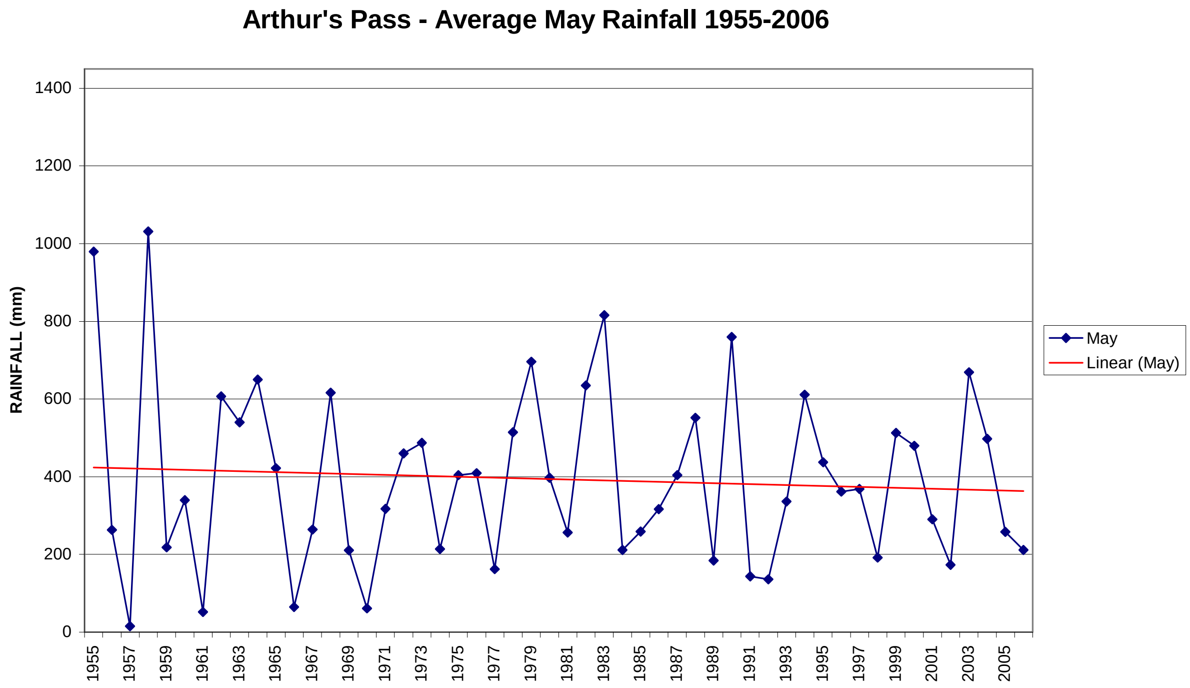
Appendix A. 8. Average February rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



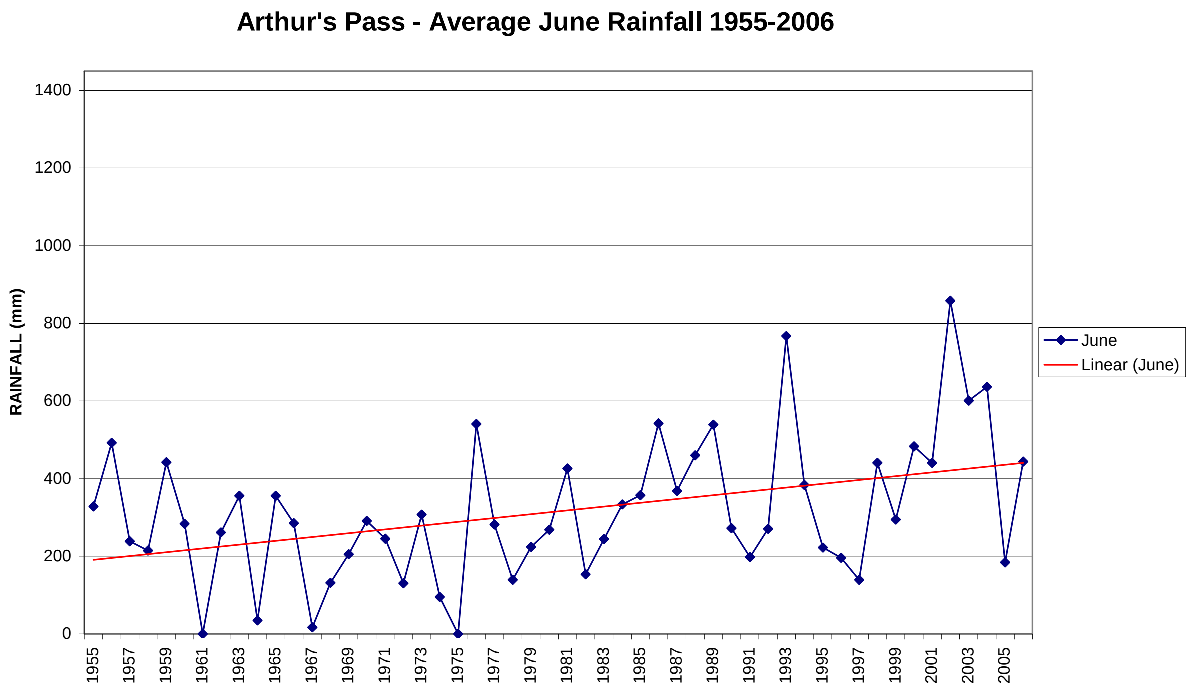
Appendix A. 9. Average March rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



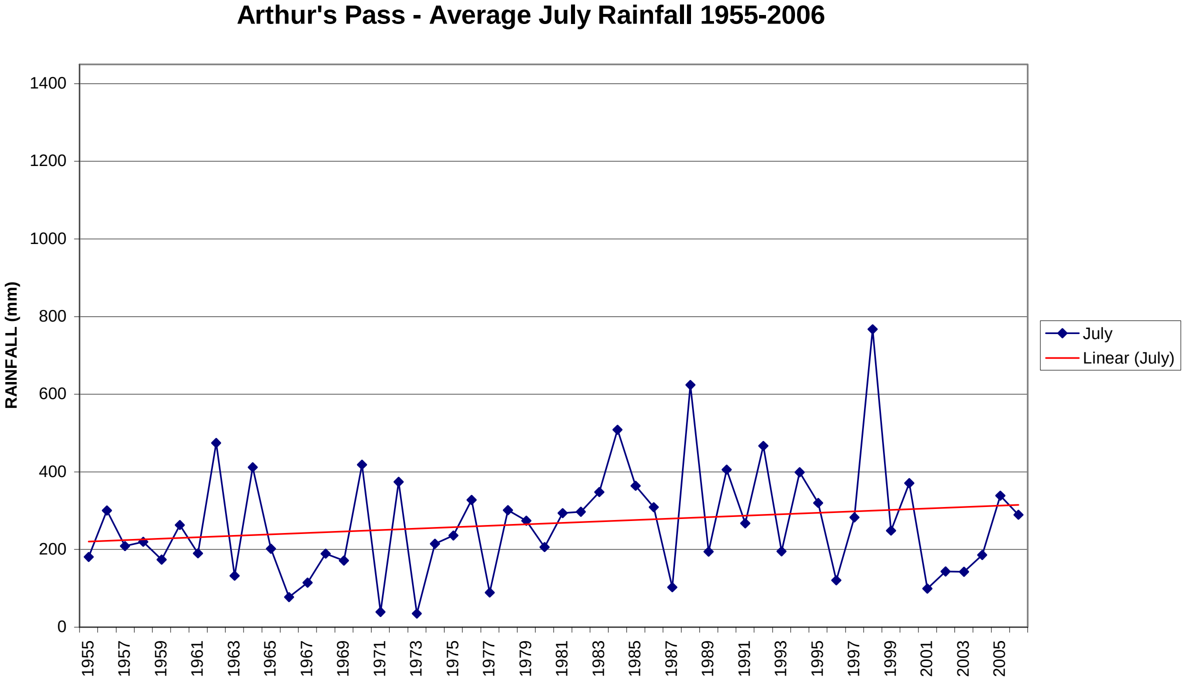
Appendix A. 10. Average April rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



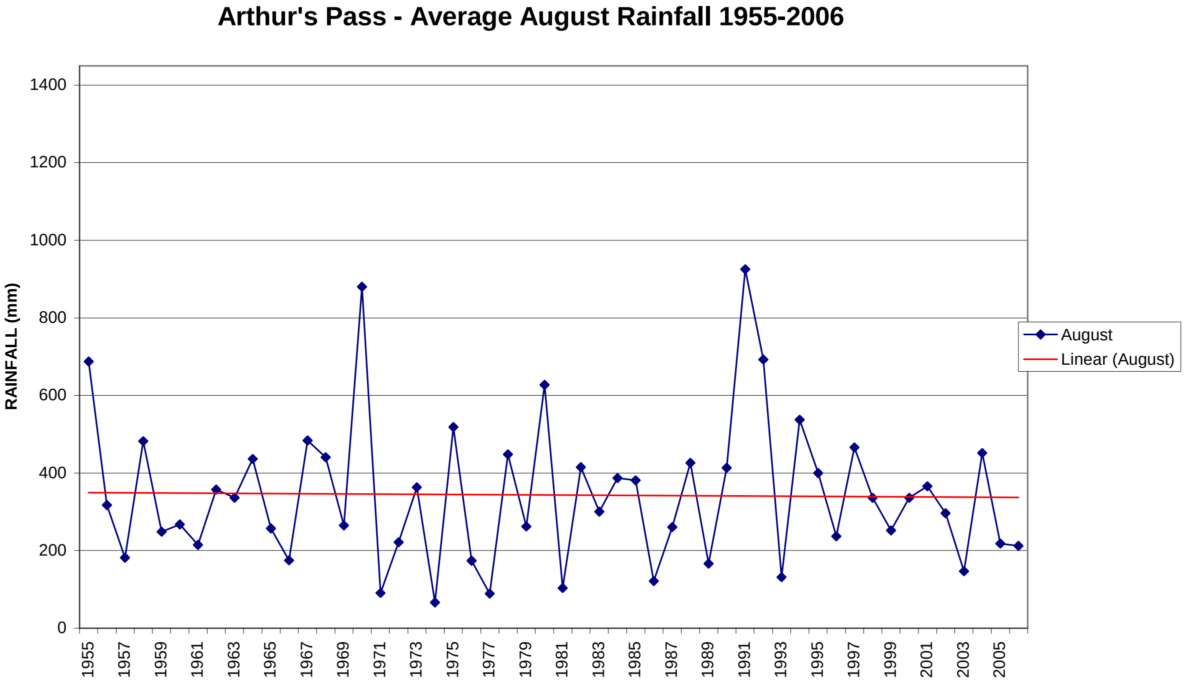
Appendix A. 11. Average May rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



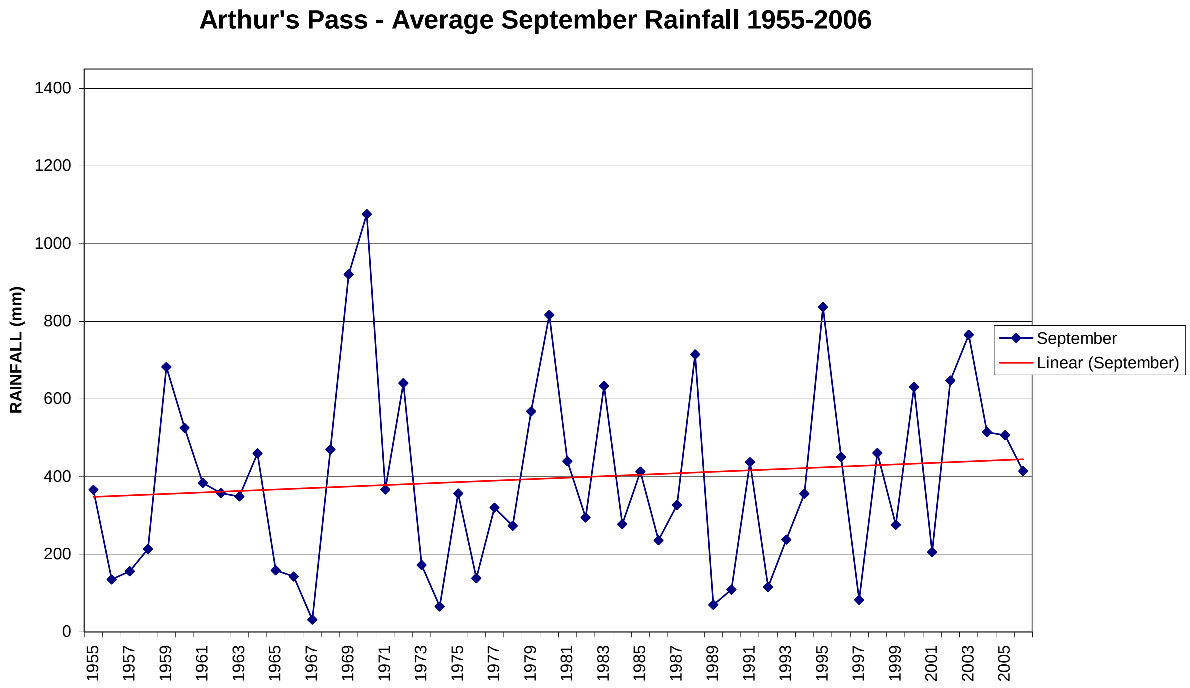
Appendix A. 12. Average June rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



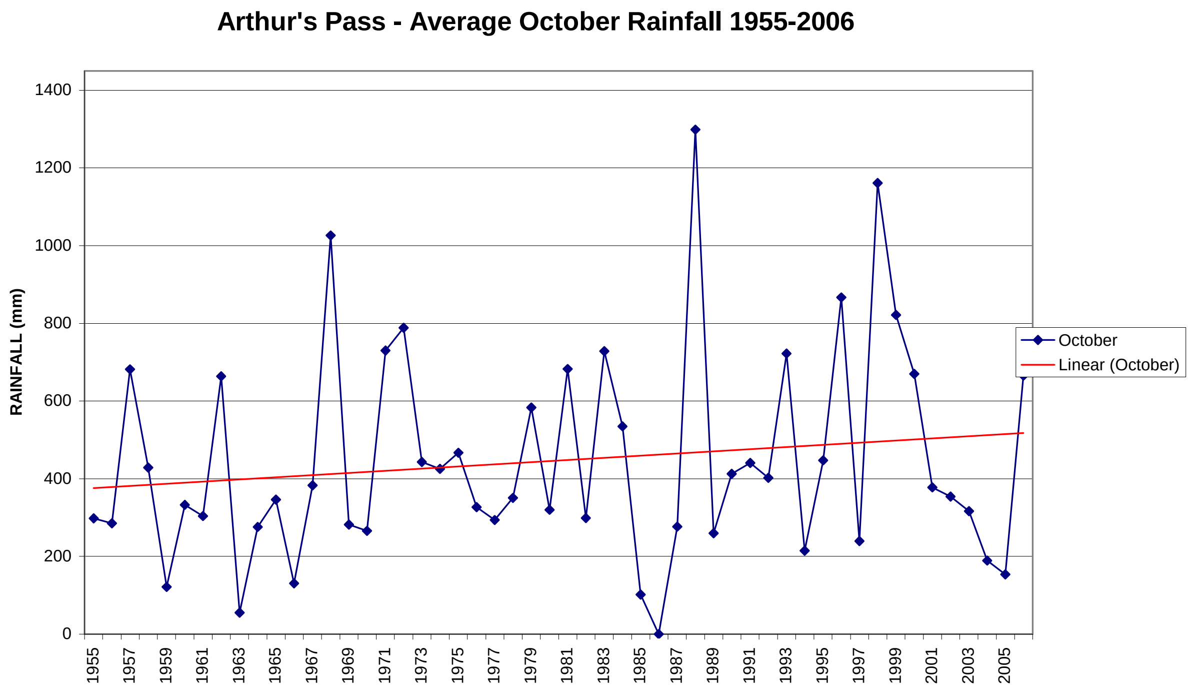
Appendix A. 13. Average July rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



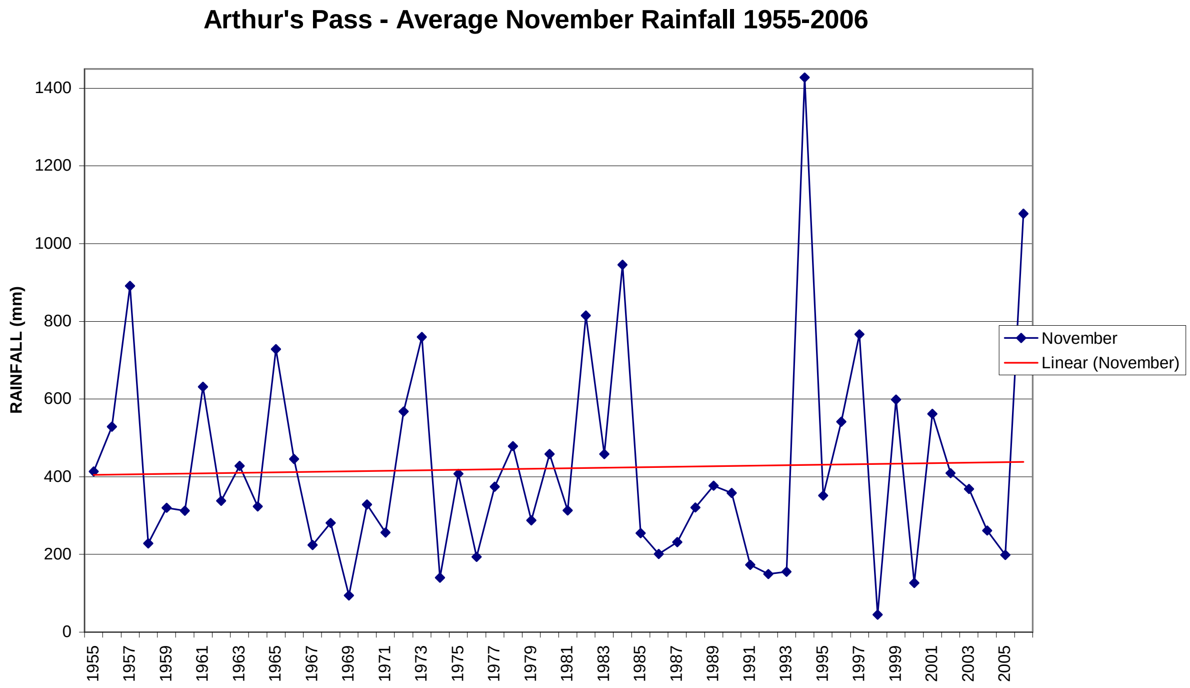
Appendix A. 14. Average August rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



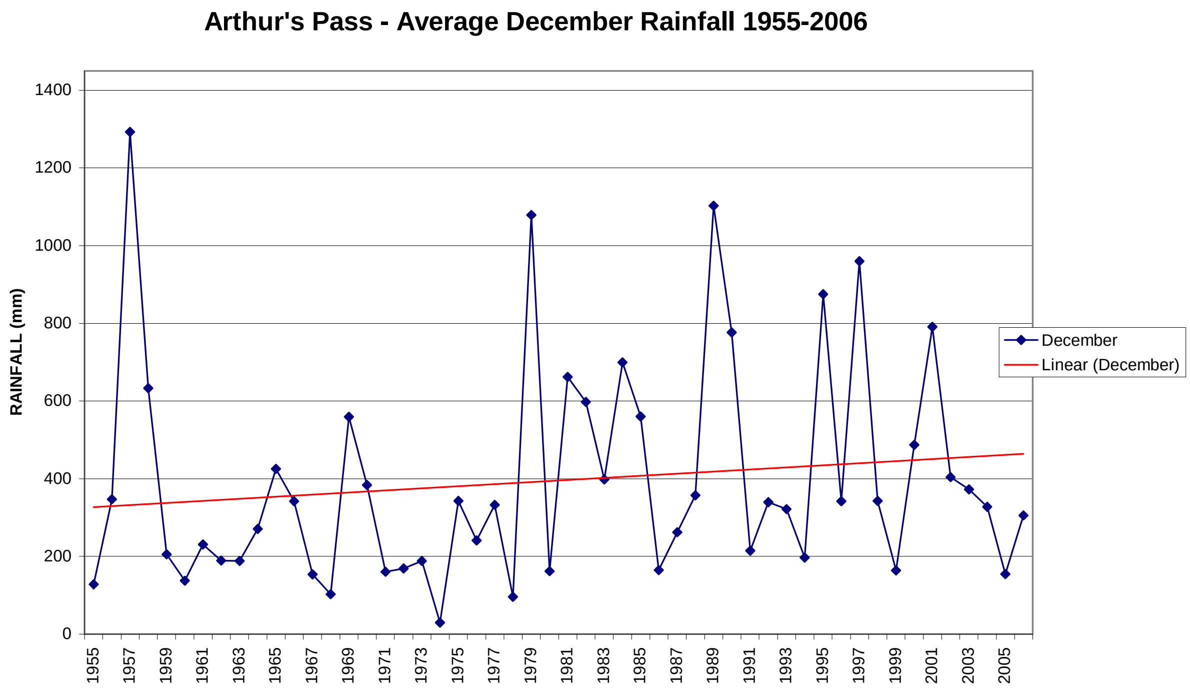
Appendix A. 15. Average September rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



Appendix A. 16. Average October rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



Appendix A. 17. Average November rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).



Appendix A. 18. Average December rainfall at Arthur's Pass from 1955 to 2006 (NIWA, 2007).

APPENDIX B

Modified Mercalli Intensity Scale

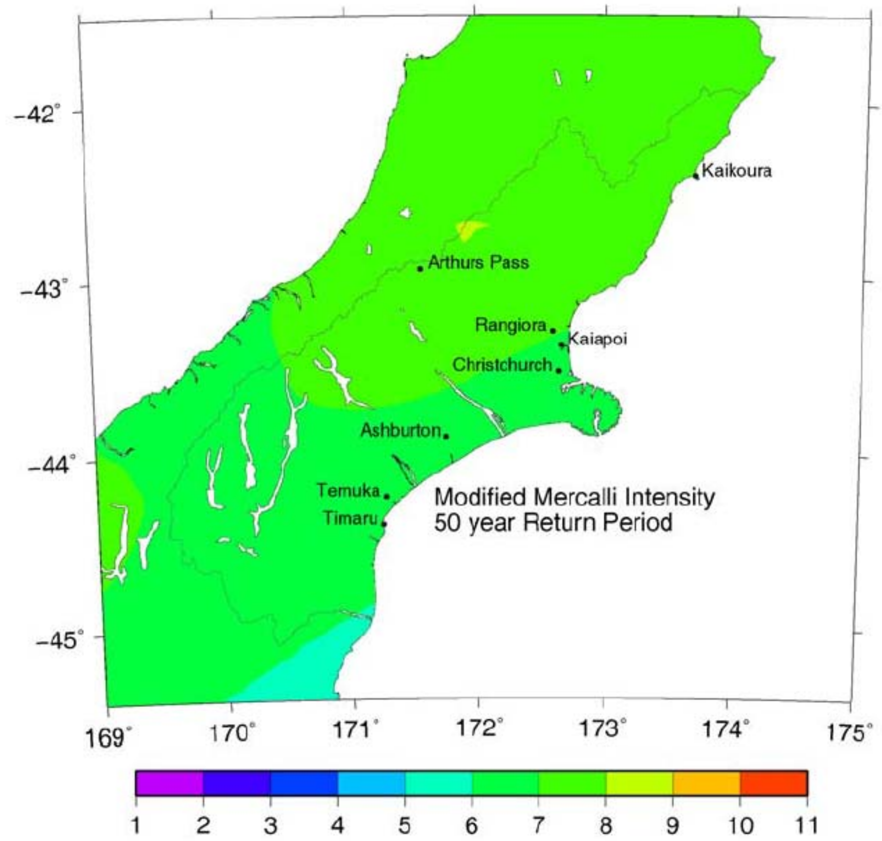
This appendix explains the Modified Mercalli Intensity Scale (MM) classification system for earthquakes, which quantifies the effects of ground shaking on objects and structures on the Earth's surface, discussed in Chapter 3. MM I represents the lowest form of gentle ground shaking, whilst MM X+ is classified as catastrophic (Duff & Holmes, 1993; K. Smith, 2004).

MM	Classification	Description of effects
I	Instrumental	Not felt by people, detected by seismographs.
II	Feeble	Felt by people at rest and in favourable locations, especially in tall buildings, some animals disturbed.
III	Slight	Small vibrations, felt quite noticeably indoors, similar to a truck passing, may not be recognised as an earthquake, possible to estimate duration.
IV	Moderate	Suspended items swing, loose items shaken, standing cars rock, walls creak.
V	Moderately strong	Felt by most people indoors and outdoors, sleepers awakened, household items displaced, doors swing open and shut, possible to estimate direction.
VI	Strong	Felt by all, difficulty walking, trees and buildings sway, suspended items swing greatly, objects dislodged and damaged, furniture moved or overturned.
VII	Very strong	General panic, difficulty standing, noticed by drivers, walls crack, masonry destabilises, slight building damage.
VIII	Destructive	Difficulty driving vehicles, masonry cracked, chimneys fall, pipes rupture, partial collapse of many buildings, houses moved on foundations, branches broken from trees, changes in flow or temperature of springs and wells, cracks in slopes and on wet ground.
IX	Ruinous	Widespread panic, houses seriously damaged, large ground fissures, underground pipes broken, damage to reservoirs, buildings shifted off foundations and timber frames warped.
X	Disastrous	Large landslides, railway lines warped, most masonry and framed buildings destroyed, serious damage to dams and embankments, ground heavily cracked.
XI	Very disastrous	Large and widespread ground fissures, few buildings remain standing, railway lines bent greatly, pipelines completely out of service, bridges destroyed.
XII	Catastrophic	Damage nearly total, waves seen on ground surface, large rock masses displaced, objects thrown into the air, lines of sight and level distorted.

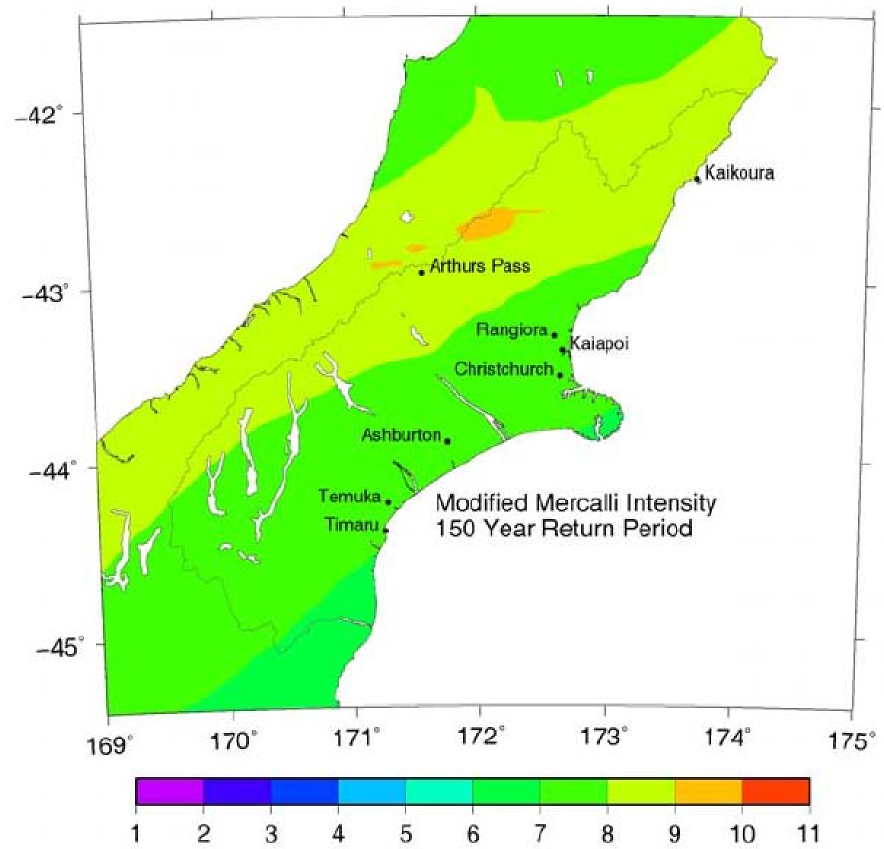
APPENDIX C

Probabilistic Seismic Estimates of Ground Shaking Intensity at Arthur's Pass

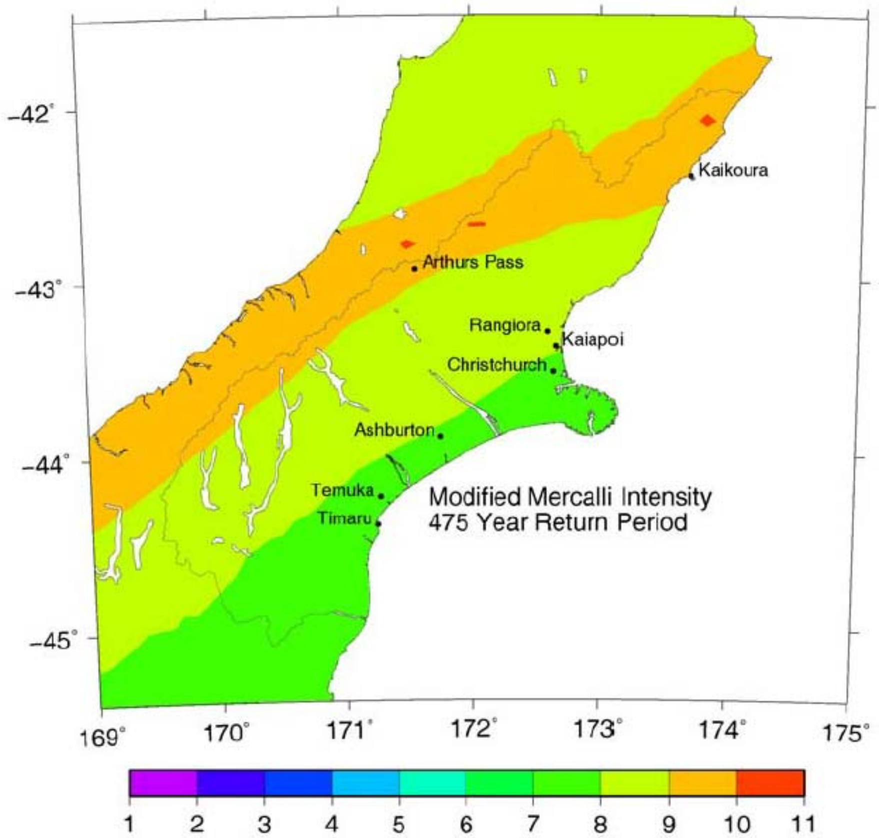
This appendix shows the most recent probability estimates for ground shaking intensity for different return periods; 50 years, 150 years, 475 years and 1000 years (Stirling et al., 2007). Because of its location close to several major plate boundary faults, Arthur's Pass lies within very close proximity to the zones of highest ground shaking intensity. This indicates that it is at high risk from seismic shaking in the future and may potentially experience ground shaking up to MM X, which is discussed in Chapter 3.



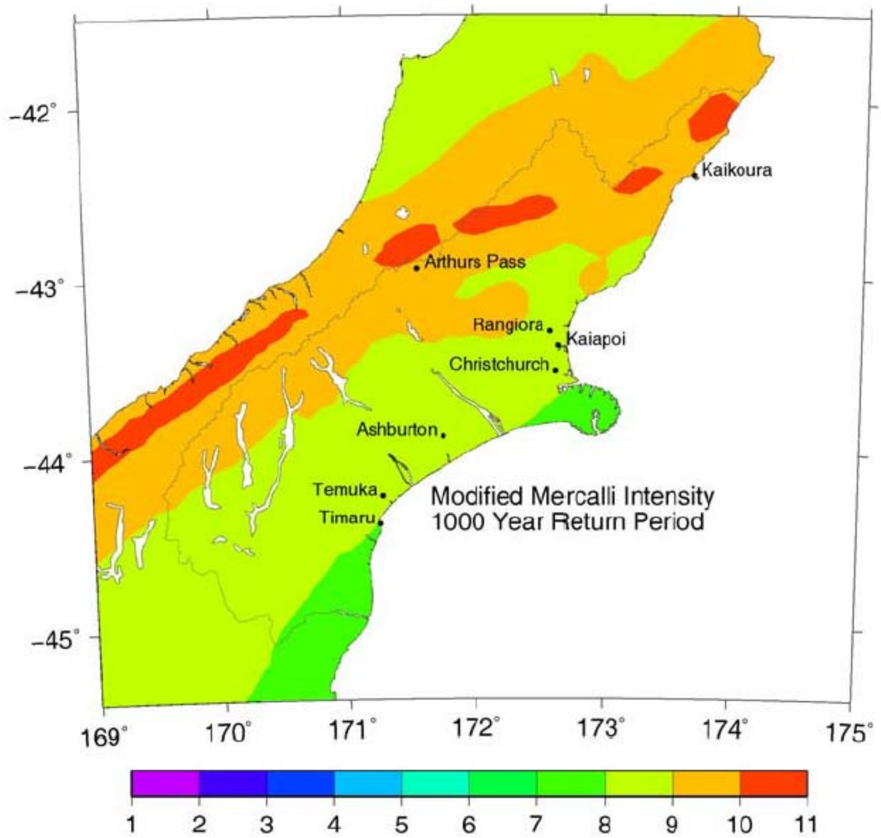
Appendix C. 1. Updated probabilistic seismic ground shaking estimate for the Canterbury region for a 50 year return interval, showing Arthur's Pass in close proximity to the zone of highest ground shaking intensity (Stirling et al., 2007).



Appendix C. 2. Updated probabilistic seismic ground shaking estimate for the Canterbury region for a 150 year return interval, showing Arthur's Pass in close proximity to the zone of highest ground shaking intensity (Stirling et al., 2007).



Appendix C. 3. Updated probabilistic seismic ground shaking estimate for the Canterbury region for a 475 year return interval, showing Arthur's Pass in close proximity to the zone of highest ground shaking intensity (Stirling et al., 2007).



Appendix C. 4. Updated probabilistic seismic ground shaking estimate for the Canterbury region for a 1000 year return interval, showing Arthur's Pass in close proximity to the zone of highest ground shaking intensity (Stirling et al., 2007).

APPENDIX D

Assessing Public Perceptions at Arthur’s Pass – Visitor Questionnaire

This appendix contains a copy of the two-page, anonymous questionnaire distributed to random participants in the Arthur’s Pass Visitor Centre. Results from the survey are discussed in Chapter 8 and were used to assess the level of natural hazard awareness that visitors have, how it contributes to the overall vulnerability of the village and how this perception may be improved.

OUESTIONNAIRE

An all hazards vulnerability assessment of Arthur's Pass, South Island, New Zealand.

Please read the following note before completing the questionnaire.

NOTE: You are invited to participate in the research project [*name of project*] by completing the following questionnaire. The aim of the project is to assess how visitors to the town perceive the natural hazard risk. The information you provide will be used to improve current methods of hazard education to the public and will contribute towards increasing visitor safety from natural hazards at Arthur's Pass.

The project is being carried out [*as a requirement for course or degree (where relevant)*] by Kate Dundas under the supervision of Associate Professor Tim Davies, who can be contacted at (03) 364 2700**.** They will be pleased to discuss any concerns you may have about participation in the project.

This questionnaire has been reviewed and approved by the Department of Geological Sciences, University of Canterbury. The questionnaire is anonymous, and you will not be identified as a participant without your consent.

You may withdraw your participation, including withdrawal of any information you have provided, until your questionnaire has been added to the others collected. Because it is anonymous, it cannot be retrieved after that.

By completing the questionnaire it will be understood that you have consented to participate in the project, and that you consent to publication of the results of the project with the understanding that anonymity will be preserved.

A natural hazard is defined as an environmental condition that has the potential to cause a disaster, which negatively affects peoples' lives, property and infrastructure such as roads, railways, electricity, communications and water supplies. Examples of natural hazards are volcanoes, earthquakes and landslides.

1. Have you seen, read or been told about any natural hazards at Arthur's Pass since you arrived in the village? If yes, please specify____________________________________

   ____

   ____

   ____

2. Did you have any prior knowledge of possible natural hazards at Arthur's Pass before arriving in the town? If yes, please specify____________________________________

   ____

   ____

   ____

   ____

3. Please rate the level of risk you think the following hazards pose to the Arthur's Pass village (0 = no risk at all, 5 = very high risk):

	NO RISK	→				VERY HIGH RISK
• Earthquakes	0	1	2	3	4	5
• Strong winds	0	1	2	3	4	5
• Thunderstorms	0	1	2	3	4	5
• Heavy snowfalls	0	1	2	3	4	5
• Snow avalanches	0	1	2	3	4	5
• Landslides and rockfalls	0	1	2	3	4	5
• Floods	0	1	2	3	4	5
• Debris flows (fast flowing, sediment-rich floods)	0	1	2	3	4	5
• River erosion (the removal of river sediments)	0	1	2	3	4	5
• River sedimentation (the build up of river sediments)	0	1	2	3	4	5

4. Have you observed any emergency evacuation plans since arriving in the town? If yes, please give details.____

____

____

5. Would you feel confident knowing what to do if a hazard event did occur in the village?____

____

____

6. Are you aware of any protective measures against natural hazards that are currently in place at Arthur's Pass?____

____

____

____

7. Do you think the hazards are well managed?______________________________

____

____

8. Are there any improvements to safety from natural hazards that you feel are necessary? i.e. better education schemes, physical barriers protecting the village, etc? If yes, please specify ____

____

____

____